MARLIN-ROCKWELL COMPANY
DIVISION OF TRW INC.

M-R-C RESEARCH PROPOSAL NO. 1540
for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

"Spin Axis Bearings"

Report - Phase V
Contract No. NAS 8-5441

December 3, 1965

Prepared by:

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/tmv

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INTRODUCTION:

Present gyro spin axis bearings are designed with a porous retainer manufactured from a paper based phenolic material. These retainers are used as an oil reservoir and are filled only once, prior to final shipment from the bearing manufacturer by vacuum impregnating the retainer with the desired oil. All retainer materials were purchased from the Synthane Corporation.

The saturated retainer is centrifuged to remove excess or surface oil. This centrifuging is required to reduce the possibility of oil flooding the gyro components, which would result in instability of the gyro assembly. Therefore, a compromise is required to have a gyro bearing with: (1) long life; (2) constant torque.

To achieve these objectives, MRC proposed the use of low energy films for coating the retainer exterior surfaces to control the migration and bleedout of the impregnated oil.

Retainers were made to the Part Print shown on page 19.

SUMMARY:

Several combinations of phenolic material, paper and resins, have been tested by a new method of determining bleed rates and patterns of oil released from the retainers. Two of these materials have absorption and bleedout rates more desirable than the retainers supplied in the 144 bearings of the NAS 8-5441 contract.

Two commercial types of resin-bonded fluorocarbon low energy films were used for coating retainer O.D.'s and faces to retard the oil bleedout. Testing of these coatings in the assembled bearing test has shown that the bleed rates of

these retainers are 20 percent less than the same type retainers without the coating. A problem of bonding the fluorocarbon to the retainer still has not been mastered. Flaking off of the fluorocarbon was noted in some tests. Whether or not this condition would have a detrimental effect on the gyro performance is only conjectural at this writing, since it has not been established whether flaking occurred during operation or during assembly.

The test procedures used in this investigation resulted in oil bleeding from the retainer 1.6X faster in the assembled bearing than it does when the retainer is rotated about its own axis at the same g-load and ambient temperature.

PROCEDURE:

Scope of Investigation:

A test fixture was fabricated which would duplicate as closely as possible the actual running of the retainer in the bearing assembly and still observe the oil bleedout patterns. (See Photo No. 1 showing the whole test rig, and Photo No. 2 showing a close-up of a portion of the rig with a retainer in a bearing assembly.)

The test fixture was designed so that:

1. 10 bearings or 10 retainers could be tested at one time.
2. Temperature could be monitored continuously.
3. External heat could be applied.
4. Speeds would be constant at 15,000 or 24,000 RPM.
5. Bearing preloading was variable.
6. Oil released from test specimens could be weighed, observed and used as museum pieces if so required.

7. Visual observations could be made during operation.
8. The fixture was small enough to be placed in a controlled environment.
9. Photographs could be taken of oil bleedout patterns. (See Photo No. 4.)

All design objectives were achieved. The outer rings were cut in half along the center of the race for assembly testing in Step #2 (see below). The retainer screening tests was divided into two steps. All retainers were subjected to Step #1 which is a means of determining what effect centrifugal force has on the impregnated or retained oil. Step #2 was a method of studying and ascertaining the bleedout patterns and rates of the retainer in an assembled bearing. Our selection of two types of retainers for testing in Step #2 was based on high absorption and low bleed out rates. All rates were based on volume and recorded as percentages. The oil used in all tests was Teresso V-78.

Step #1 and Step #2 tests were conducted on normal impregnated retainers and on retainers which had been coated with low energy films in an attempt to control bleedout. Testing of normal, uncoated retainersis referred to as Section A in the text. Testing of coated retainers is referred to as Section B.

The procedure for testing retainers in Step #1 follows:

1. The retainers were impregnated with oil per MRC Spec. Sheet 1540-A (attached page 14, Steps 1 thru 6). Sheet 1540-A reveals the entire procedure for retainer processing in this contract, Phase I, II, and III.

2. All retainers were then placed in a dessicator for storage and transport. The dessicator was used to reduce the possibility of the retainer absorbing moisture from the atmosphere.

3. The test rig without retainers was pre-run for 24 hours to stabilize the temperature at 160°F.

4. The test rig was stopped and the test retainer was placed on the arbor. (See Photo No. 3.) It was secured by lightly tightening the screw on the retainer face. There was a diametrical clearance of .001" between arbor O.D. and retainer I.D.

5. A clean clear glass vial or bonnet with an I.D. of 23 mm was placed over the retainer to be tested as shown, MRC Dwg. #R-52004-E, page 15. All oil which leaves the retainers during spin tests was collected on the vial ID. The vials were used to ascertain bleed rates and patterns as described in items 9 and 10.

6. The drive motor was started and time recorded.

7. The retainer was spun at 15,000 RPM for 24 hours. The RPM equals the rotational speed of retainer in the bearing assembly.

8. The drive motor was stopped and the vial and retainer were placed in the dessicator.

9. The vial was weighed and weight recorded. Other data such as oil droplet sizes, distance between rows of droplets, photos taken, are on file in our records.

10. All oil was removed from vial I.D. and the vial weighed again. The difference between the weight of vial with oil and weight of vial with the oil removed is the value used to determine bleed rate of the retainer.

Assembly of the test fixture for Step 2 is shown in MRC Dwg. R-52004-1E, page 16. The testing sequence was as follows:

1. Retainers were impregnated with oil per MRC Spec. Sheet 1540-A, Steps 1 thru 6.
2. All bearing components were cleaned, stored and transported in a dessicator.
3. The bearing was matched to the proper contact angle.

   The outer ring had been cut in half along the center of the race so that oil bleed out patterns can be monitored more closely.
4. Test rig without retainer was pre-run for 24 hours to stabilize temperature.
5. Complete test bearing was assembled into the test rig.
6. Preload was applied through hole and spring in the shaft (MRC Dwg. R-52004-1E).
7. A clean and clear glass vial or bonnet was placed over the bearing to catch the oil as it is released from the rotating bearing assembly.
8. The drive motor was started and the time recorded. RPM of the driven outer ring was 24,000 RPM.
9. Test was terminated after 24 hours.
10. The vial and retainer were placed in the dessicator.
11. The vial weight was measured and recorded. Other data such as oil droplet sizes, distance between rows of droplets and photos were taken. All data are on file in our records.

12. All oil was removed from vial I.D. and the vial weighed again. The difference between the weight of the vial with oil and weight after cleaning off the oil is the value used to determine bleed rates of the retainer.

Material Testing - Step 1, Section A

There were 100 retainers fabricated in 10 lots of 10 specimens each. Only 5 retainers from each lot, however, were tested in Step 1. During the testing in Step 1, Section A, we observed that there were two rows of oil droplets on vial I.D.'s. The distance between these rows was equal to the diameter of the ball pockets.

Retainers are listed in order of best absorption and lowest bleedrates in the following TEST DATA, and not in chronological order.

TEST DATA

#1 - MRC Lot#S-92413-2

Material: (a) XX Natural Tubing from .004" thick International Mills Paper

(b) Normal Specific Gravity - 1.17 min.

(c) Resin 2681

Results: Absorption - Low 4.0%
High 5.4%
Ave. 4.4%

Bleedout - Low 5.5%
High 18.0%
Ave. 10%

#2 - MRC Lot #S-92412-2

Material: (a) XX Natural Tubing from .004" thick International Mills Paper

(b) Low Specific Gravity = less than 1.17

(c) Resin 2681

Results: Absorption - Low 3.7%
High 5.0%
Ave. 4.1%

Bleedout - Low 8.7%
High 18.0%
Ave. 13.0%

#3 - MRC Lot #S-92414-2

Material: (a) Tubing from .004" thick Krafelt Paper

(b) Normal Specific Gravity = 1.18 min.

(c) Resin 2681

Results: Absorption - Low 1.9%
High 2.7%
Ave. 2.3%

Bleedout - Low 7.0%
High 12.0%
Ave. 12.2%

#4 - MRC Lot #X-50709-1

Material: MRC MS-A02 (supplied in Phase I, II & III bearings this contract)

(a) Tubing from .004" thick Krafelt Paper

(b) Normal Specific Gravity = 1.18 min.

(c) Resin 1680

Results: Absorption - Low 4.1%
High 4.5%
Ave. 4.3%

Bleedout - Low 18.0%
High 23.0%
Ave. 21.0%

#5 - MRC Lot #S-92416

Material: (a) LBB-3 Tubing - Cotton fabric weight 3 oz. per sq. yd.
Thread count 96 x 100

(b) Normal Specific Gravity - 1.25 min.

(c) Resin 4869

Results: Absorption - Low 2.2%
High 3.9%
Ave. 3.4%

Bleedout - Low 16.0%
High 29.0%
Ave. 22.0%

#6 - MRC Lot #S-92412-1

Material: (a) XX Natural Tubing from .004" thick Krafelt Paper

(b) Normal Specific Gravity = 1.17 min.

(c) Resin 2681

Results: Absorption - Low 1.9%
High 2.6%
Ave. 2.1%

Bleedout - Low 16.0%
High 32.0%
Ave. 22.0%

#7 - MRC Lot #S-92413-1

Material: (a) XX Natural Tubing from .004" thick International Mills Paper

(b) Normal Specific Gravity = 1.17 min.

(c) Resin 3112

Results: Absorption - Low 1.3%
High 1.4%
Ave. 1.37%

Bleedout - Low 28.0%
High 40.0%
Ave.35.0%

#8 - MRC Lot #S-92414-1

Material: (a) Tubing from .00275" thick Krafelt Paper

(b) Normal Specific Gravity = 1.22 min.

(c) Resin Mixture of 3913 and 2681

Results: Absorption - Low 0.5%
High 1.1%
Ave. 0.8%

Bleedout - Low 51.0%
High 91.0%
Ave. 63%

#9 - MRC Lot #S-92412-3

Material: (a) XX Natural Tubing from .004" thick International Mills Paper

(b) High Specific Gravity = 1.22 min.

(c) Resin 2681

Results: Absorption - Low 0.7%
High 1.3%
Ave. 1.0%

Bleedout - Low 14.0%
High 30.0%
Ave. 20.0%

#10 - MRC Lot #S-92415

Material: (a) XX Natural Sheet stock from .010" thick Krafelt Paper

(b) Normal Specific Gravity = 1.32 min.

(c) Resin 2026

Results: Absorption - Low 0.3%
High 0.6%
Ave. 0.46%

Bleedout - Low 79.0%
High 100.0%
Ave. 90%

This material had the best visual appearance when viewed under a microscope at 30X magnification.

Step #1, Section B Testing

Three coatings were applied to the O.D. and faces of standard retainers in an attempt to control bleedout rate. These were commercially available coatings, two of which were resin bonded low energy films and the other was a varnish. Test conditions were the same as that in Step #1. In the first three tests, coatings were applied before vacuum impregnation.

MRC Lot #X-50709-1

Trade name of coating: Emralon 310 (Product of Acheson Colloids)

Results:	Absorption	- Low	3.3%		
		High	4.9%		
				Ave.	4.1%
	Bleedout	- Low	1.5%		
		High	3.5%		
				Ave.	2.5%

MRC Lot #X-50709-1

Trade name of coating: Emralon 315 (product of Acheson Colloids)

Results:	Absorption	- Low	4.3%		
		High	4.4%		
				Ave.	4.35%
	Bleedout	- Low	3.0%		
		High	7.0%		
				Ave.	3.5%

MRC Lot #X-50709-1

Trade name: Durad Fungus and Moisture Resistant Varnish Y-169
(product of Maas & Waldstein, Newark, N. J.)

Results:	Absorption	- Low	1.6%		
		High	3.1%		
				Ave.	2.35%
	Bleedout	- Low	2.0%		
		High	25.0%		
				Ave.	14.0%

To determine the most advantageous sequence of operation with Emralon 310, further tests were performed. Again, only the retainer O.D. and faces were coated. Results were as follows:

MRC Lot #X-50709-1

Coated before impregnation

Results:	Absorption	- Low 2.2%		
		High 3.0%		
			Ave.	2.6%
	Bleedout	- Low 16.0%		
		High 16.4%		
			Ave.	16.2%

No flaking off of the green Emralon 310 was noted.

MRC Lot #X-50709-1

Coated after impregnation

Results:	Absorption	- Low 3.4%		
		High 3.8%		
			Ave.	3.6%
	Bleedout	- No oil droplets found under 50X magnification. This verified previous testing at M-R-C.		

Analysis of tests from Step 1, Sections A and B indicated that retainers from Lot #S-92413-2 should be coated with Emralon 310 after oil impregnation and tested in Step 2.

Step #2 Tests

The first tests in this step were conducted to determine what effect rotating balls would have on the oil bleedout rates of retainer materials tested in Step #1. The lots of retainers were:

MRC Lot #S-92412-2

Results:	Absorption -	Low	4.1%	
		High	4.3%	
				Ave. 4.2%
	Bleedout -	Low	18.5%	
		High	24.5%	
				Ave. 21.5%

MRC Lot #S-92413-2

Results:	Absorption -	Low	4.2%	
		High	4.4%	
				Ave. 4.3%
	Bleedout -	Low	14.0%	
		High	25.0%	
				Ave. 20.0%

Note: (1) These retainers had an average difference in bleed rates of 3% as tested in Step #1. They have an average difference of 1 1/2% in this testing.

(2) Bleedout rate of these retainers is approximately 1.6 times greater than it was in Step #1, so a rotating and spinning ball in the retainer ball pocket acts like a pump on the impregnated oil.

As previously stated in the analysis of Step #1, Sections A and B, retainers from Lot #S-92413-2 were impregnated and coated with Emralon 310. For a comparison additional retainers from the Lot #X-50709 were also processed and tested under Step #2, Section B conditions.

MRC Lot #X-50709-1

Coating: Emralon 310 .001" thick

Results:	Absorption	- Low	4.6%		
		High	4.6%		
				Ave.	4.6%
	Bleedout	- Low	11.0%		
		High	13.0%		
				Ave.	12.0%

Note: The Emralon coating has reduced the bleedout of these retainers 9% below the bleedout rate of the retainers in Step #1 testing. Total reduction of oil bleedout of these retainers based on tests in a bearing would be 1.6 x 21% - 12% = 21% reduction.

MRC Lot #S-92413-2

Coating: Emralon 310 .0005" thick

Results:	Absorption	- Low	3.0%		
		High	3.1%		
				Ave.	3.05%
	Bleedout	- Low	11%		
		High	19%		
				Ave.	14%

Note: The Emralon coating had come off the O.D. of the retainer in various areas. The coating has, however, retarded the bleedout 6% when compared to same tests run in Step #2 without coating.

Although the discharged particles of coating had not obviously interferred with bearing operation, this is a highly unsatisfactory condition. This method of controlling bleed rate cannot be used for bearings in gyros until the possibility of coating loss is eliminated. The results of the limited testing to date indicate that this is a fruitful area for further work.

M-R-C Specification Sheet 1540-A
RETAINER PREPARATION AND LUBRICATION

(As supplied under N.A.S. Contract #8-5441)

1. Retainer Cleaning - The retainer shall be thoroughly cleaned of foreign material and residue. The cleaning process shall not physically or chemically damage the retainer.

2. Retainer Drying - Immediately prior to lubricant impregnation, the retainer shall be thoroughly vacuum dried to insure the complete removal of moisture.

3. Retainer Dry Weight - Immediately following the vacuum dry operation, record the retainer weight on the data sheet (W_1).

4. Impregnation - The following limits were conformed to during the impregnation process.

   (a) Vacuum - The vacuum shall not exceed 0.10 microns of Hg at 70°F or 250 microns of Hg at 170°F. (Assume a straight line relationship for other temperature-vacuum values.)

   (b) Temperature - The temperature shall not exceed 225°F.

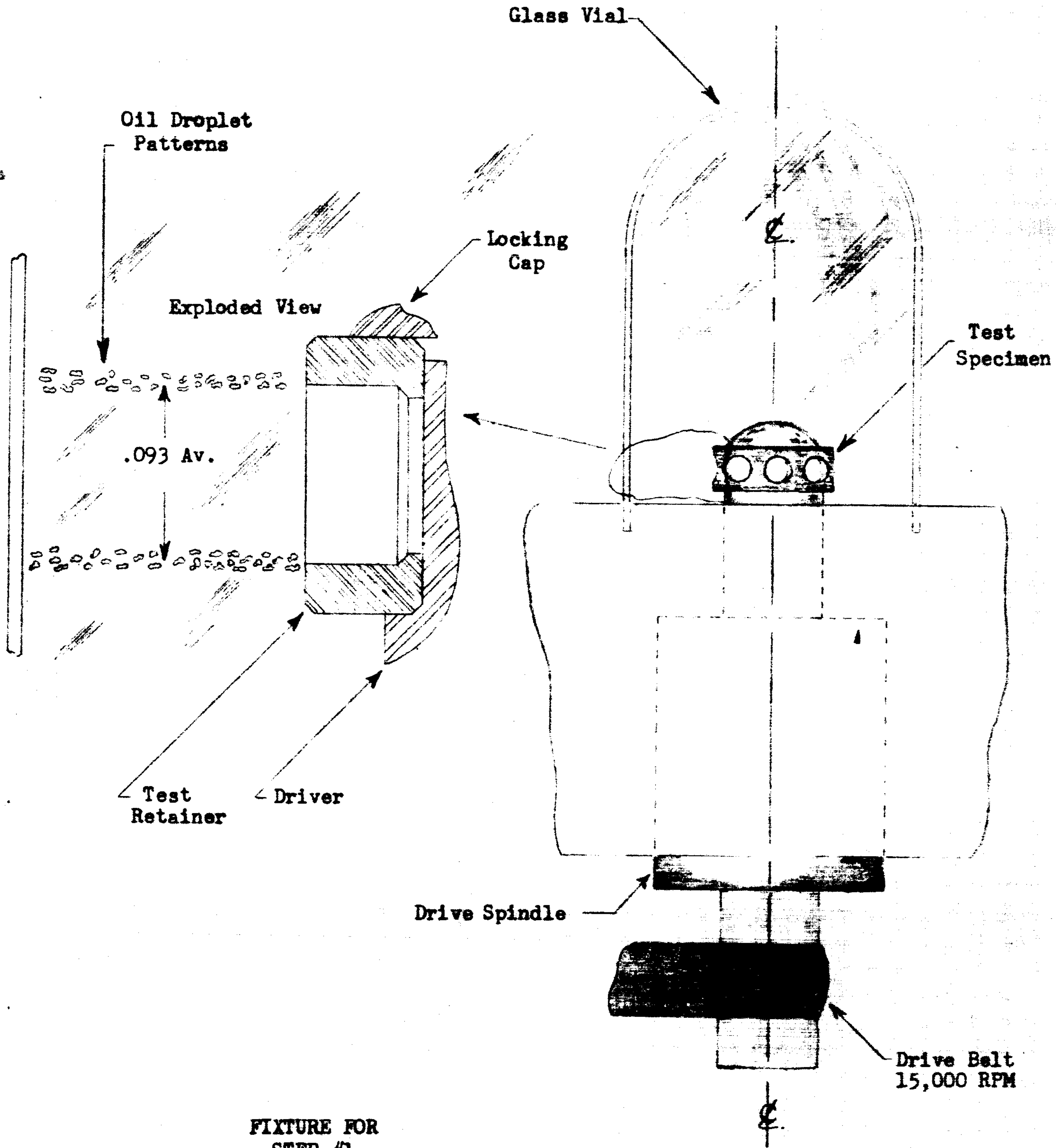
5. Absorbed Oil - After impregnation, the retainer shall be centrifuged at 400 G's for 5 minutes at room temperature. Immediately following the 400 G centrifuge operation, determine the total weight of the retainer and absorbed oil (W_2). The weight of absorbed oil is W_3 and is recorded on the data sheet: $W_3 = W_2 - W_1$.

6. Oil Retention - The percent of oil retention is equal to $\frac{W_3}{W_1} \times 100$ and is recorded on the data sheet.

7. Retained Oil - After the 400 G centrifuge and determination of the weight of absorbed oil, the retainer shall be centrifuged at 650 G's for 5 minutes at room temperature. Immediately following this 650 G centrifuge operation, determine the weight of the retainer and the retained oil (W_4). The weight of retained oil is W_5 and is recorded on the data sheet: $W_5 = W_4 - W_1$.

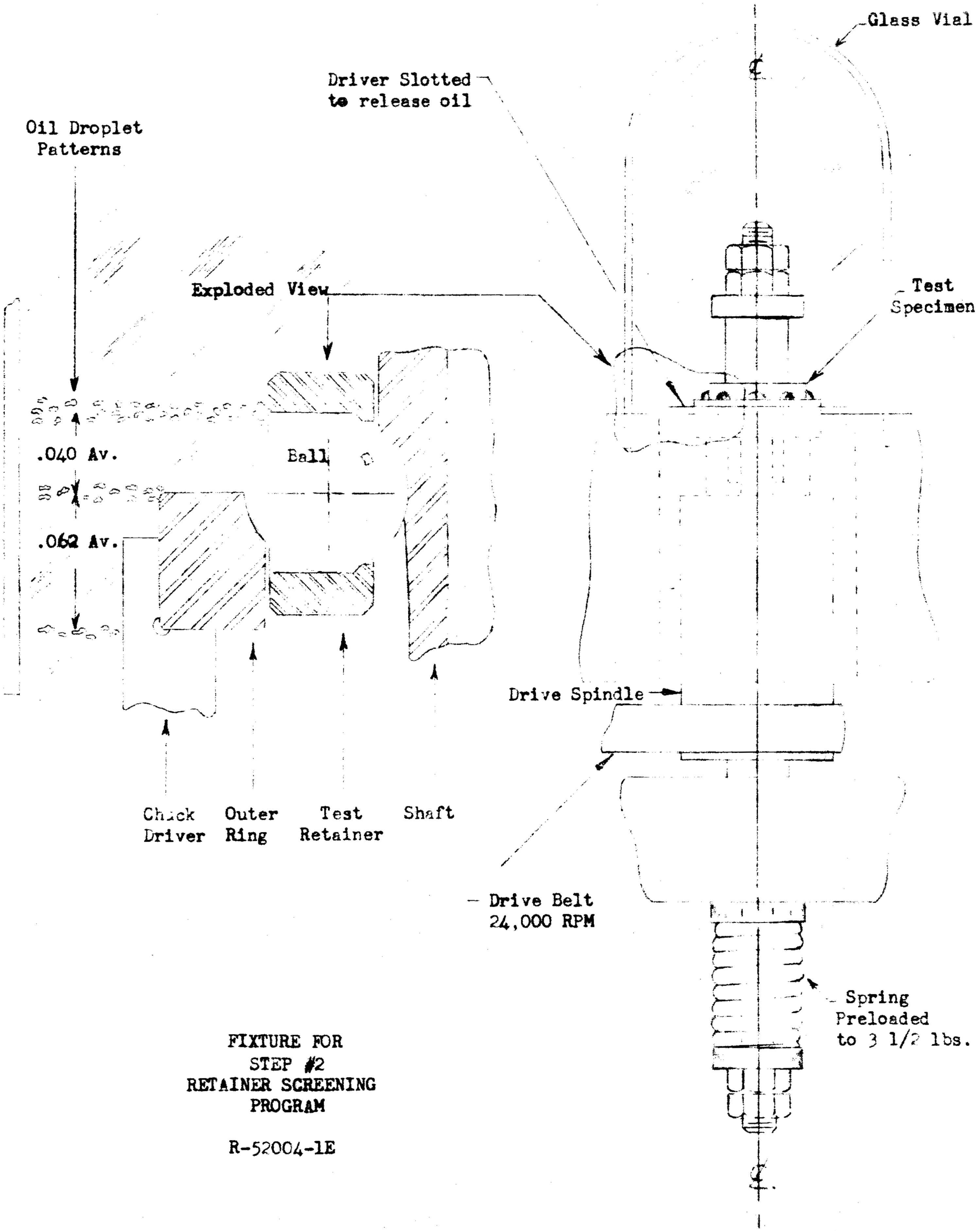
8. Oil Bleedout - The percent of oil bleedout is equal to $\frac{W_3 - W_5}{W_3} \times 100$ and is recorded on the data sheet.

9. Reimpregnation - In the event that the subsequent processing changes the amount of oil retention, the retainer shall be reimpregnated immediately and centrifuged at 400 G's prior to packaging.



FIXTURE FOR
STEP #1
RETAINER SCREENING
PROGRAM

R-52004-E



FIXTURE FOR
STEP #2
RETAINER SCREENING
PROGRAM

R-52004-1E

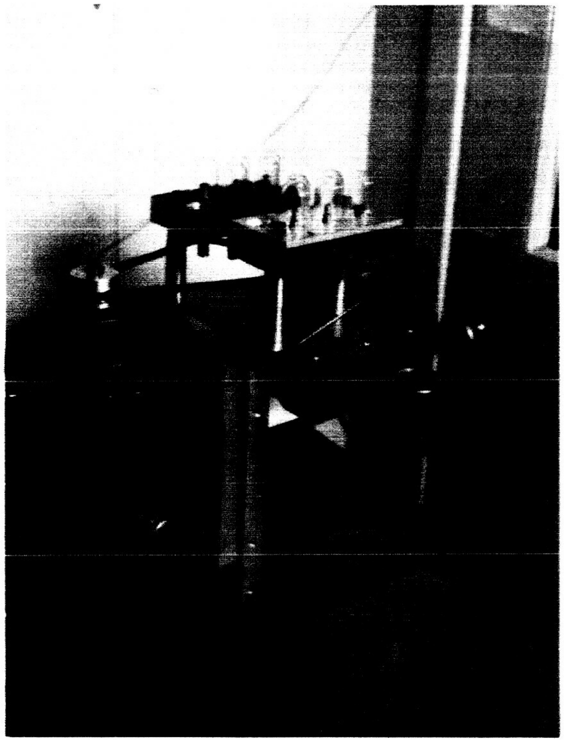


PHOTO NO. 1
Multiple Spindle Test Rig
(Set-up for rotating retainers, Step #1 conditions)

PHOTO NO. 2
Close-Up View of Test Rig Showing Retainer
Assembled in a Bearing, Step #2 Conditions
(Bearing has half of outer removed.)

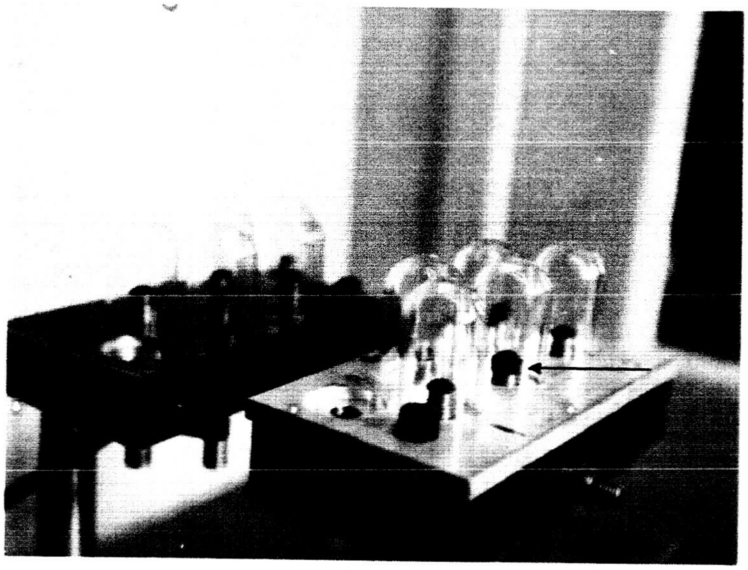


PHOTO NO. 3
Close-Up View of Test Rig Showing Set-Up for
Step #1 Conditions
(Arrow points to retainer)

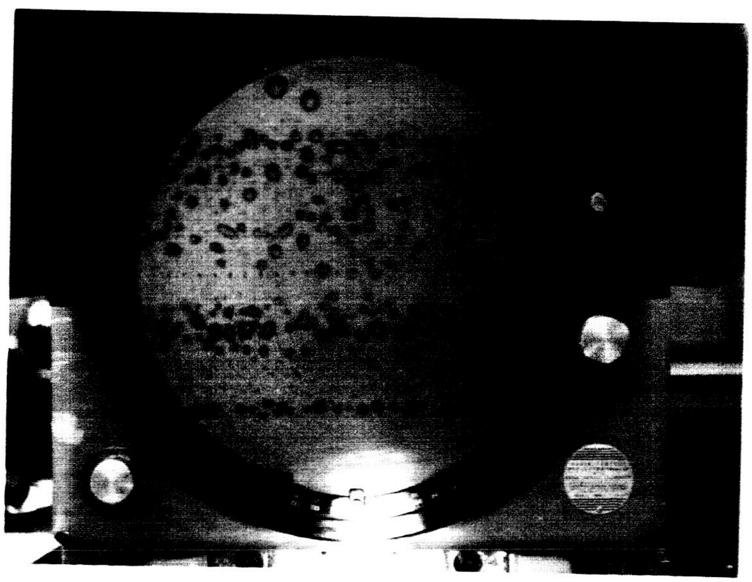


PHOTO NO. 4
Magnified View of Retainer Bleed Out Pattern
(Actual droplet size varies from .003" to .020" diameter.)

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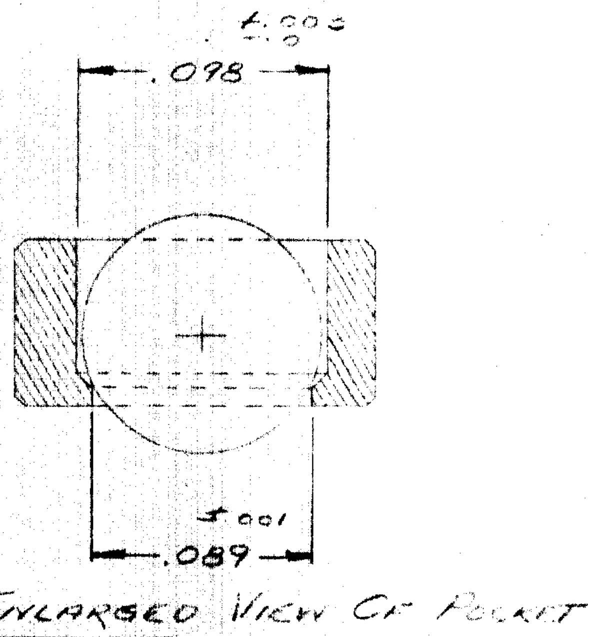

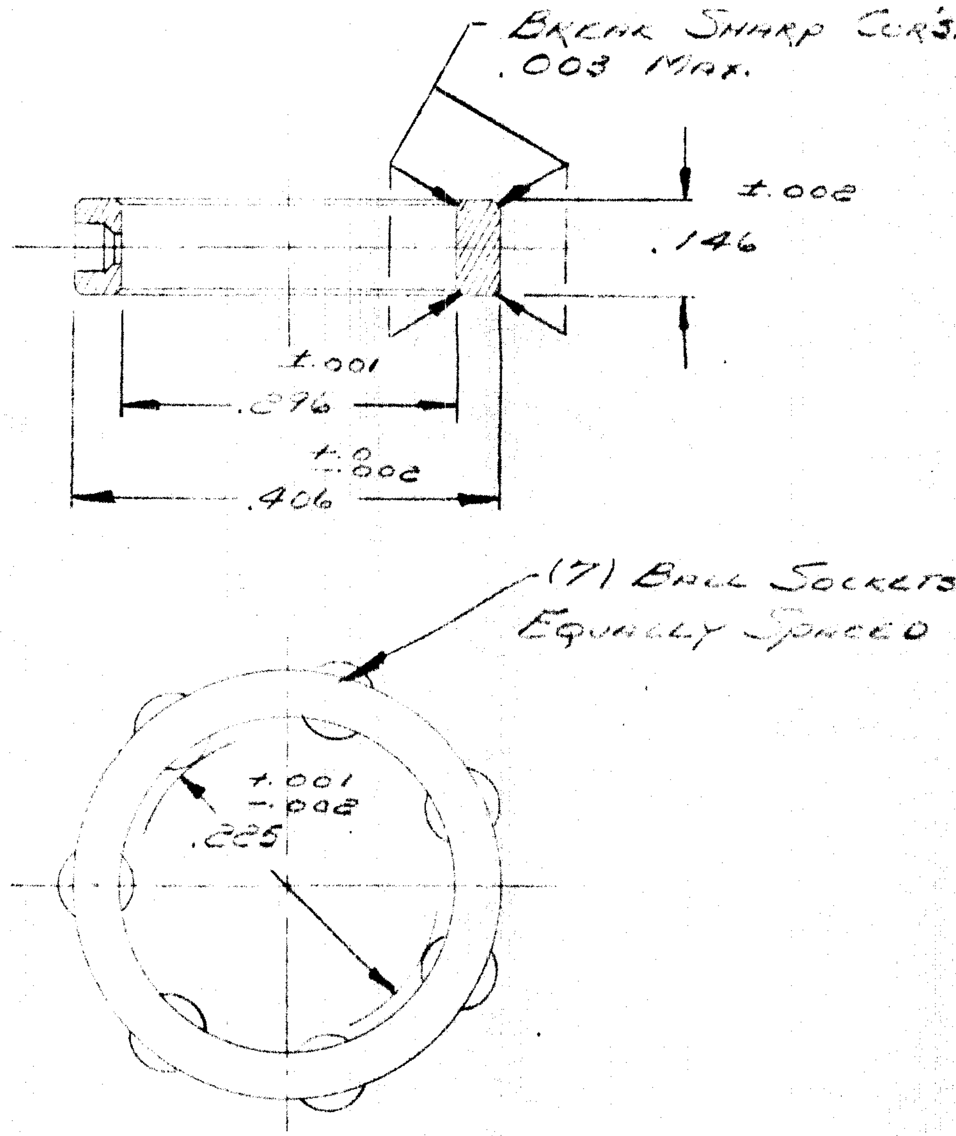

TOLERANCES
Unless Otherwise Specified

FRACTIONS $\pm\frac{1}{64}$
DECIMALS ±.005
ANGLES ±½°

DO NOT SCALE DRAWING
Break All Sharp Edges
Except Cutting Edges

SUPERSEDES	DATE
SUPERSEDED BY	DATE

DRAWN	CHECKED	APPROVED
DATE	DATE	DATE

MARLIN-ROCKWELL CORPORATION Jamestown, N. Y. Form 356

MRC BALL AND ROLLER Bearings

RETAINER FOR CONTRACT NAS 85941
BRG. Nº X54200 & X54201

REV

N66 35016

Summary Report
Contract No. NAS 8-5441
Phases I, II, III, IV, and V of
M-R-C RESEARCH PROJECT NO. 1540

"Spin Axis Bearings"
for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA

June 27, 1966

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Manager
Research and Development

/tmv

ABSTRACT:

Twelve experimental lots of spin axis bearings, involving nine different raceway finishes, were manufactured by MRC under sponsorship of NASA, George C. Marshall Space Flight Center. Following dynamic testing of the bearings in gyro assemblies, Marlin-Rockwell Company personnel took part in the post mortem analyses of bearing failures. From the combination of knowledge of manufacturing techniques, documentation of prerun and postrun bearing measurements, life test data, and failed bearing analyses, it has been possible to arrive at the following conclusions:

1. Three methods of finishing spin axis bearing raceways produce superior performance and life under marginal lubrication conditions.

2. Bearing life cannot be correlated with high luster (light reflectivity) under magnified visual observation nor with geometry of the race in the low microinch range.

3. Measurement data from instruments such as the Wavometer, Anderometer, Profilometer, and Proficorder are most useful for process and contamination control and historical records, rather than as the final criteria for predicting bearing life. However, these values can be utilized with more consistent results than possible with a control by visual specifications only.

4. Bearings with unidirectional, circumferential surface finish lay performed better than those with irregular or cross-the-race lay.

Additional work was done on controlling the oil bleed rate from the impregnated retainers. The results demonstrate the promise of this approach toward improving bearing life, but further development is necessary before it can be incorporated into operational gyros.

INTRODUCTION:

This work is a part of NASA's search for more reliable, longer-lived aerospace components. A most critical spacecraft component is the gyro. These instruments provide the stable reference axes from which all directions and attitudes are measured, once the spacecraft is in flight. Consequently, a spacecraft guidance system cannot perform its function without properly operating gyros.

A gyro consists of a small, high speed electric motor, mounted on a spin axis bearing. The bearing is a two row unit with inner races normally ground into an integral shaft. The outer race rotates. All lubrication for the bearing is provided by bleedout of oil from the previously impregnated retainers. The basic requirements for spin axis bearing operation is that its torque and drift rate must be very low. Any appreciable change in bearing torque constitutes failure.

The existing spin axis bearing is a culmination of a great deal of development work on race geometries and oil impregnated retainers. However there has still been wide variations in individual performance and no clear understanding of roles which various parameters play. NASA sponsored this program to determine the effect of various race surface finishes and lays on bearing performance.

Raceway finish was believed to affect spin axis bearing operation in a number of ways. First of all it was recognized that the basic geometry of the surface must be conducive to smooth, practically frictionless rotation. Because of this, raceway finish methods which produce a high luster have been favored. This may be considered a "cosmetic" approach. However, a very shiny finish can be created by methods which promote metal smearing or surface lamination. During bearing operation, a surface including smeared metal can breakdown, creating roughness. An extremely lustrous finish may not support a hydrodynamic oil film as well as slightly rougher surfaces. In addition, the role of the finish in catalysing lubricant deterioration is not fully understood.

Because of the subjective nature of visual examination for surface finish quality, bearing manufacturers use vibration measuring and profile measuring instruments to gauge effects of various processes. The quantitative data derived by these means permit more objective comparison of finishing methods, but none of the measured parameters correlates concisely with actual gyro bearing life. It was hoped that this program might overcome the existing lack of correlation because of the high degree of documentation and the deliberate variation and innovation which were provided in raceway finishes.

The basic objective of the program was achieved. Certain raceway finishes were demonstrated to produce consistently long life and certain general treatments were proved superior to others. In spite of a very thorough documentation, however, it has not been possible to correlate specific instrumentation readings with life. One basic cause of this is the extremely small range of values permissible in geometry or vibration levels for spin axis bearings. Instrument noise at 50,000 amplification on the Proficorder, for example, tends to obscure surface finish variations of a few microinches. Also, there is no way of microscopically examining the surface of a spin axis bearing outer race without sectioning the ring. Hence, metallographic examination of bearings before test was necessarily limited to inner rings and balls.

PROCEDURE:

The manufacturing program was set up to provide twelve lots of twelve bearings each, divided into three phases.

Bearings conformed to GCMSFC's drawing number GC 425376. Outer and shaft are shown on Marlin-Rockwell Company Drawing numbers R51891-1E and R51891-2E, respectively. These bearings are designated X54200 by Marlin-Rockwell Company. See pages 5 and 6. Design contact angle is $28^{\circ} \pm 1^{\circ}$, with no variation greater than 30' in one assembly.

Phase I consisted of the production of one lot, manufactured and finished to Marlin-Rockwell Company's established procedure for spin axis bearings.

Phase II and Phase III bearings were all produced from the same heat of 52100 consumable electrode vacuum melt steel for inners and outers. These components were treated as a single lot up to the final raceway finishing process. Then the shafts and outers were divided into eleven equal lots by random selection. It was found that a single size of ball would fit all bearings. Therefore, all balls were from the same heat of steel and same ball-lap load. All retainers were made from the same lot of phenolic material. In this way the variables between lots were reduced to those induced by race finishing procedures.

Phase II consisted of finishing eight lots using a different method for each lot. After these had been completed, they were assembled in gyros and run in dynamic tests, at Eclipse-Pioneer Division of Bendix Corporation under NASA sponsorship. Those finishes which performed most satisfactorily were then incorporated into the three remaining lots of bearings (Phase III).

Each finish has been designated by a letter of the alphabet. Phase I bearings, the reference lot, is referred to as Lot A and its finish as "A". The eight lots of Phase II are referred to as Lots B through I, with corresponding finish

R51891-1E

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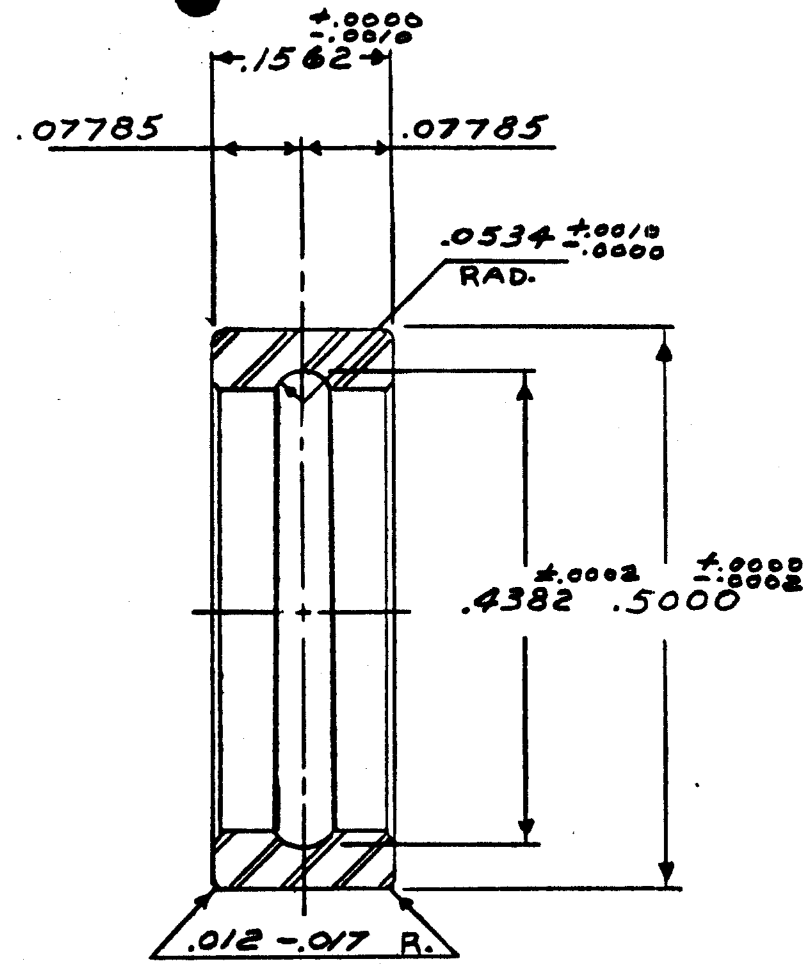


MATERIAL SHAFT- SAE 52100 STEEL. (MS-30)

TOLERANCES
Unless Otherwise Specified

FRACTIONS ± 1/64
DECIMALS ±.005
ANGLES ±½°

DO NOT SCALE DRAWING
Break All Sharp Edges
Except Cutting Edges

SUPERSEDES	DATE
SUPERSEDED BY	DATE

DRAWN	CHECKED	APPROVED
R. Paul	H. Munson	H. Munson
DATE 12/23/63	DATE 12-23-63	DATE 12-23-63

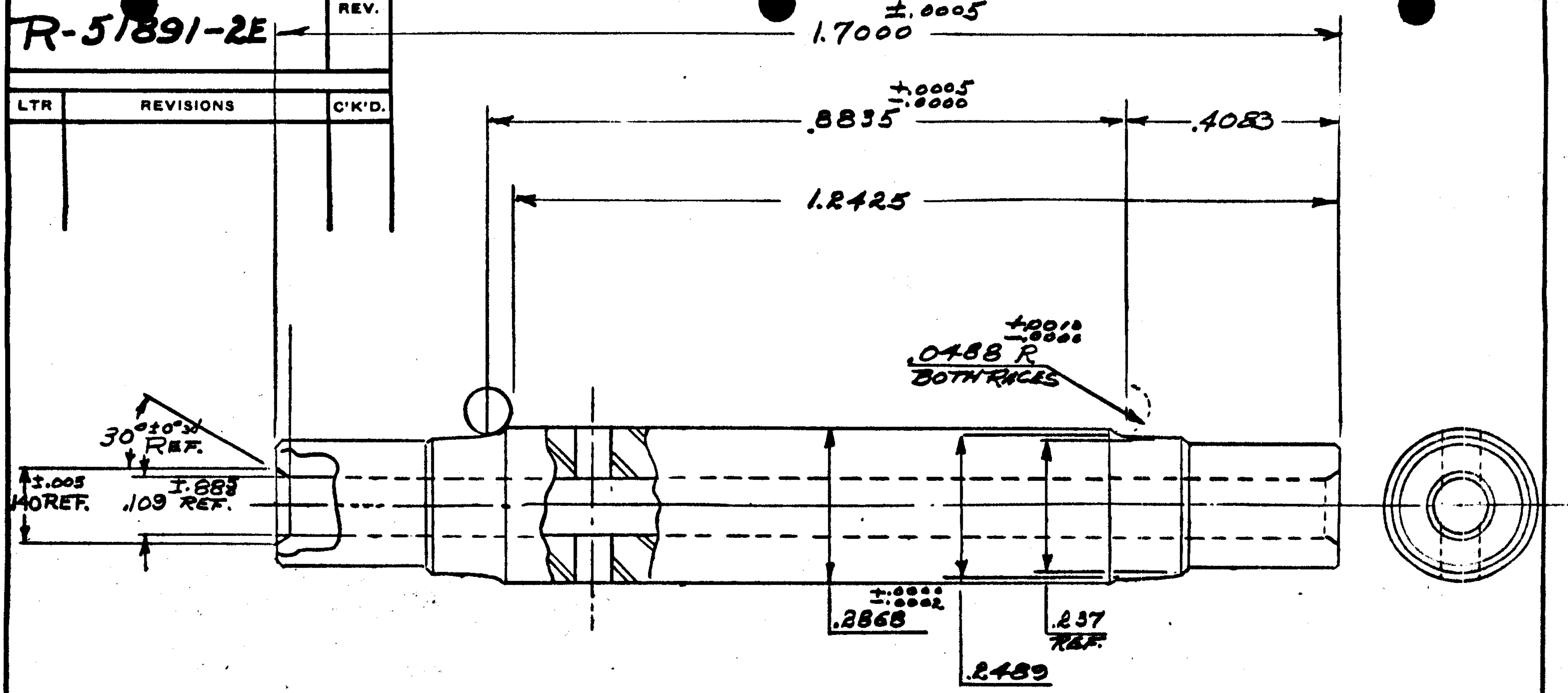
MRC BALL AND ROLLER Bearings

MARLIN-ROCKWELL CORPORATION Jamestown, N. Y. Form 356

OUTER X54200 R51891-1E REV.

R-51891-2E

LTR	REVISIONS	C'K'D.	REV.



MATERIAL : SHAFT - SAE 52100 STEEL (MS-30)

TOLERANCES
Unless Otherwise Specified

FRACTIONS ± 1/64
DECIMALS ± .005
ANGLES ± ½°

DO NOT SCALE DRAWING
Break All Sharp Edges
Except Cutting Edges

SUPERSEDES	DATE
SUPERSEDED BY	DATE

MARLIN-ROCKWELL CORPORATION   Jamestown, N. Y.   Form 356

DRAWN	CHECKED	APPROVED
R. Paul	H. Munsen	H. Munsen
DATE	DATE	DATE
12-23-63	12-23-63	12-23-63

MRC BALL AND ROLLER bearings

SHAFT ~ X54200 | R 51891-2E | REV.

designations. Since the Phase II bearings were subjected to the same finishing procedures as certain of the Phase II lots, there are no new designations in this group, except that one lot received a combination of two different processes and the effect is referred to as "DB finish".

One item which has received considerable attention is the effect of contamination of raceways by embedded residue from polishes, etc. Such residue may contribute to roughness and break loose during dynamic operation, resulting in increased torque. This material may also catalyse a chemical reaction within the oil, resulting in polymerization and ultimate loss of lubrication. To check this possibility, samples of all finishing abrasives were obtained and rolled between hardened pieces of 52100 steel. The resulting embedding was studied under polarized light and photographed at 100X to 200X magnification. With this information as reference, all inner races were examined for abrasive contamination under polarized light and high magnification. Since the only way that the outer rings could be so examined required cutting them into pieces for viewing, sample rings were finished for each lot and destructively examined.

A large number of finishing processes were considered before the eight of Phase II were selected. Before a raceway finishing method was approved, a complete analysis was made on a pilot lot of four bearings by the various quality control techniques used at Marlin-Rockwell Company. Although this method was time consuming, it eliminated many of the originally proposed processes. For example, electrochemical machining was considered, but tests indicated that geometry variations were far too wide for gyro quality.

Individual races were measured for waviness and variation between "peaks" and "valleys" in the finish by Wavometer and Profilometer which have visual read-outs, and Proficorder. The Proficorder produces a chart with one-dimensional amplification up to 50,000X and has become Marlin-Rockwell Company's standard instrument for final check-out of waviness and surface finish for both profile and circumferential measurements. To assure the reliability of this instrument, a 11/32" diameter ball was set aside and checked on the Proficorder after the measuring of each lot of bearings. It was found that instrument noise and lack of resolution tend to obscure the tiny differences between specimens. In addition, the continuing checks of the "Master Ball" reveal variation in Proficorder signal for the same input.

An Anderometer was used to measure noise level or vibration. This instrument measures radial displacement of the outer ring when the shaft is turned at 1800 RPM under light thrust load. Three separate band-pass filter circuits tend to segregate the various vibration components which contribute to overall noise. It was found that minimum noise does not correlate with longest life.

As bearing Lots A through I were completed they were shipped to NASA, Huntsville. The individual bearings were assembled into gyros and tested by Eclipse-Pioneer Division of Bendix Corporation. The scope of Marlin-Rockwell Company's work was increased to provide for analysis of failed bearings and to study means of controlling the bleed rate of oil impregnated retainers. (This work is designated, Phase IV and Phase V respectively). On the basis of life test data plus examination, it was possible to assign ranks to the individual finishes and to specify finishes for the three lots of Phase III.

The first lot of Phase III bearings combined the desirable geometrical characteristics of Lot D with the finish produced in Lot B, and hence was designated "DB". The other two lots, were identical in finish to Lots I and C, respectively, and serve the additional purpose of proving the repeatability of the process controls over an elapsed period. About 18 months passed between the finishing of Lots C and I in Phase II and Lots C-2 and I-2.

The various surface finish methods may be described as follows:

Lot A - Races were string polished with 700 grit abrasive.

Lot B - Races were string polished with 700 grit abrasive. This surface finish was identical with that of Lot A. However, Lot B bearings incorporated an attempt at improved geometry through the use of an improved center hole grinder.

Lot C - Races were honed across the race (perpendicular to the direction of a rolling ball) using a honing stone containing a mixture of 900-1200 grit.

Lot D - Races were honed around the race (parallel to the direction of a rolling ball) using a honing stone containing a mixture of 900-1200 grit.

Lot E - Races were honed around the race using a honing stone containing 1500 grit.

Lot F - Races were honed at an angle to the direction of the race so that a cross-hatch pattern was produced on the race. The pattern had an included angle of 60° with center lines parallel to the direction of a rolling ball on the race. The honing stone contained a mixture of 900-1200 grit.

Lot G - Races were tumbled with Carbo-Brite No. 6 chip.

Lot H - Races were first string polished with 700 grit abrasive. Following polishing, races were shot peened by Metal Improvement Company, Hackensack, N.J. Glass shot size was .0021-.0029" with peening done at an Almen intensity of 008N2.

Lot I - Races were string polished by 700 grit abrasive, then Harperized. In the latter process, rings were tumbled in Titan 28 abrasive under a 22G load.

Lot DB - Races were first subjected to the D-type finish with the around-the-race honing. The B-type string polish was then applied to the races.

Lot C-2 - Races received the C-type finish.

Lot I-2 - Races received the I-type finish.

In all finishes, with the exception of type G, stock removal averaged .00015" to .0003" on diameter.

RESULTS AND DISCUSSION:

Proficorder charts, photographs of magnified race surface areas, and measurement data, are included in the Appendix to this report. The polar Proficorder charts shown are from one representative bearing from each lot. The surfaces of both inner raceways of a shaft are traced on the same chart. One of the outer races and the external surface of the same ring are traced on another chart. Surface irregularities are magnified so that each radial spacing equals .000005".

The Proficorder trace permits measurement of surface finish roughness and waviness, plus eccentricity and out-of-roundness. The individual charts are marked indicating the specific out-of-roundness (abbreviated O.O.R.) and eccentricity (abbreviated ecc.) for the particular bearing. Eccentricity of an outer race refers to its relationship to the bearing O.D., while the eccentricity of the shaft raceways refers to their relationship to each other.

Highly magnified photographs of all finishes (except A which is basically the same as B) are presented along with the representative Proficorder charts. Each photograph is of an inner raceway, since it is impossible to obtain a straight-on view of an outer race without sectioning the ring. The original photographs were taken by Eclipse-Pioneer Division of Bendix Corporation, and have proven very valuable in analysing the effect of different processes on surface finish.

The linear Proficorder charts, Appendix pages A-30 through A-32 demonstrate the changes produced by various processes on Lot DB. The photographs on page A-29 demonstrate the effect pictorially.

Measurement data and average endurance lives of all lots are included on page A-39 of the Appendix. "High" and "Low" listings on the table indicate highest and lowest readings obtained from process control and final assembly instruments for any bearing in the particular lot. Roughness is defined as peak to valley variation with a .030" cut-off around-the-race. Variations which require an interval of more than .030" to complete are defined as waviness.

Retainer data on page A-39 refer to oil retention and bleed-out of bearing retainers. The procedure for impregnating a retainer with oil and for centrifuging the excess is described on MRC Specification Sheet 1540-A, page 14 of attached "Report - Phase V."

Life test data on individual bearings, as reported by Eclipse-Pioneer Division of Bendix Corporation, are listed below. Included with them, where possible, are primary causes of failure, as determined by MRC personnel in post-mortem analyses.

LIFE TEST DATA

Bearing No.	Hours Life	Remarks
A-1	4063	Suspended without failure
A-5	3174	Failed primarily due to contamination
A-6	22	Failed prematurely, not examined by MRC
A-9	4135	Failed primarily due to contamination
A-11	3328	Failed primarily due to contamination
B-1	780	Failed primarily due to lack of lubrication
B-2	362	Test stopped because of noise in bearing, cause indeterminate
B-3	2814	Failed primarily due to retainer failure
B-5	12620	Failed - not yet examined by MRC
B-7	556	Failed primarily due to contamination
C-5	4505	Still running, 6-10-66
C-6	10447	Still running, 6-10-66
C-7	10474	Still running, 6-10-66
C-9	11133	Still running, 6-10-66
C-11	0	Test stopped because of noise, caused by raceway finish
D-2	2273	Failed, primarily due to contamination
D-3	402	Failed, primarily due to contamination
D-4	1550	Failed, primarily due to contamination
D-6	3440	Failed, primarily due to contamination
D-8	0	Test stopped, bearing was damaged (brinelled)prior to te
D-10	1420	Failed, cause indeterminate

Bearing No.	Hours Life	Remarks
E-2	937	Failed, primarily due to damage (brinelling)
E-7	595	Failed, primarily due to contamination
E-8	0	Test stopped, bearing was damaged (brinelled)
F-1	0	Failed due to raceway finish
F-2	98	Failed due to raceway finish
F-9	0	Failed due to raceway finish
G-1	40	Failed due to raceway finish
G-2	357	Failed due to raceway finish
G-5	1038	Failed due to raceway finish
H-2	400	Failed due to raceway finish
H-3	107	Failed due to raceway finish
H-5	455	Failed due to raceway finish
I-3	8404	Still running, 6-10-66
I-4	3789	Failed primarily due to raceway finish as indicated by high readings on Anderometer Low Band.
DB-4	2204	Still running, 6-10-66
DB-6	2200	Still running, 6-10-66
DB-7	1127	Still running, 6-10-66
DB-8	1525	Still running, 6-10-66
(C-2)-21	1301	Still running, 6-10-66
(C-2)-22	2120	Still running, 6-10-66
(C-2)-26	1223	Still running, 6-10-66
(C-2)-29	2379	Still running, 6-10-66

In arriving at the average lives shown on page A-39 of the appendix, the following bearings have been omitted: A-6, C-11, D-8, and E-8. Cause of the infant failure of A-6 is unknown. Bearing C-11 was rejected at Eclipse-Pioneer because of a high noise level, which was caused by the raceway finish. Whether or not this bearing would have operated satisfactorily is not established. It had relatively high Anderometer readings, but no higher than those of bearing C-9 which is still running satisfactorily. Bearings D-8 and E-8 both were damaged prior to test.

No average life value is feasible for Lot B because of the tremendous range of lives and the number of failures unrelated to raceway finish. The average life for Lot E is probably unreliable, due to damage to two of the bearings after shipment from Marlin-Rockwell Company.

The significance of contamination as a cause of spin axis bearing failure cannot be readily assessed, particularly in a raceway finish evaluation. For purposes of this comparison it is assumed that some contamination after the bearing leaves the manufacturer is a normal hazzard, and that a bearing must be able to withstand it. It is reasonable to assume that some raceway finishes will tolerate a limited quantity of foreign material while others will not. Therefore all bearing failures which include contamination as primary cause are included in rating the finishes, although some units may have been subjected to a fairly large amount.

It is impossible to test these bearings dynamically without introducing extraneous factors. In this regard it would be of interest to test bearings at more than one facility, to see if the same finishes react in the same general manner under different assembly procedures.

It has not been possible to correlate specific measurements and instrumented data with long bearing life, although some parameters appear critical if certain limits are exceeded. The limiting values for the apparently significant parameters are not clearly defined; indeed, the true cause of short bearing life is probably an interaction between two or more parameters. Unfortunately it has not been possible to test even half of the bearings dynamically. However, examination of data sheets for individual tested bearings generally reveals no reasons for differences in life between specimens in the same lot. (Bearing C-11 is a possible exception since its geometry and noise level were poorer than averages for the lot.)

There is little correlation between average torque measurements of assembled gyros and lot life in this program. The lot with highest average torque (Lot F) did have shortest life but the lot with the next-to-the-highest torque (Lot D) performed moderately well. Also, one of the poorest lots (Lot H) had one of the lowest torques.

In general, Lots D and E had the best geometry as evidenced by Out-of-Round, Eccentricity, and Wavometer measurements. Lot E bearings showed poor life while Lot D performance was moderate. Lot C had the poorest geometry, on the basis of Out-of-Round and Eccentricity readings. However, Lot C bearings have very good life. It seems obvious that, within the range of values observed in this program, Out-of-Roundness and Eccentricity values are not significant.

The lots with rough finishes and multidirectional lays performed poorly. These bearings had highest readings for Roughness, Wavometer High Band, and Anderometer Medium and High Band. In each case the average readings for these lots were two or more times those of any of the other lots. Within the more normal range of values for these parameters it is not feasible to rank the various finishes.

Lot DB combined the excellent geometry of the D-type finish with the smooth, lustrous finish of Lot B. Results to date are promising, in that there are no early failures but are too incomplete to permit ranking.

During the course of this program, some bearings attained many thousands of hours life and some lots were consistent in this regard. It appeared that further major improvement in life is dependent on lubrication. Unfortunately, the total amount of lubricant available for these spin-axis bearings is a very few milligrams. Examination of tested bearings suggested that only a part of the theoretically available oil ever is used as a lubricant. Oil migration out of the retainer-to-ball-to-raceway lubrication cycle can be a cause for gyro instability and can promote contamination. It is logical that bearing life can be greatly extended if the available oil can be forced to bleed into the ball contact areas at a controlled rate.

Phase V of this program was set up to investigate the problem. The results of the work have been reported previously but are included as a separate section of this

Summary Report. Further investigation is continuing under Phase VI, to be reported at a later date.

CONCLUSIONS:

While testing is not complete, and there are a number of variables in testing which color results, finishes may be ranked as follows, from best to poorest:

C, I, B or A, D, E, G, H, F

Bearing life cannot be correlated with high luster nor with geometry of the race in the low microinch range. The B-type finish has the highest luster while Lots D and E have the best geometry, but Lot C has the best life. The irrelevance of geometry (in the low microinch range) to life is aptly demonstrated by the fact that Lot C generally had the poorest Out-of-Round and Eccentricity measurements of all.

Unfortunately it is impossible to rate Lot DB at this time. This finish combines the excellent geometry of Lot D with the fine B-type finish.

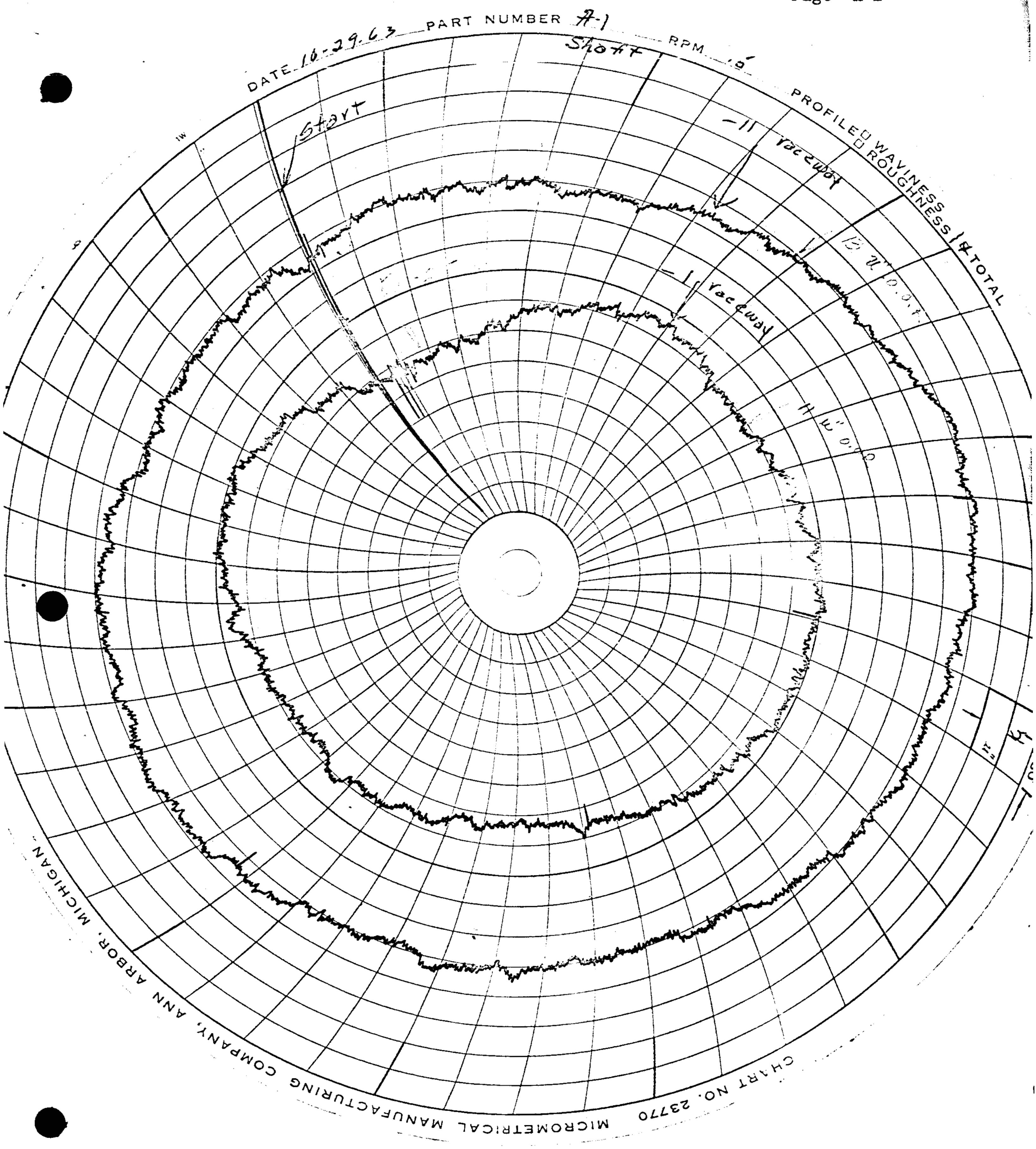
The production of Phase III bearings has demonstrated the ability to reproduce specific bearing finishes over an elapsed time.

Bearings with unidirectional circumferential finish lay performed much better than those with irregular or angular lay. Performance of Lots F, G, and H was very poor.

Further work is necessary in the area of controlled lubricant bleed rate for spin axis bearings. If the objectives of this work can be accomplished it will provide a major break-through in extending gyro life.

The coordination between bearing manufacturer, gyro manufacturer, and NASA, which took place in this program has been most helpful in furthering spin axis bearing technology. The free exchange of ideas which has occurred among the various agencies has resulted in a greater understanding by all concerned.

A P P E N D I X



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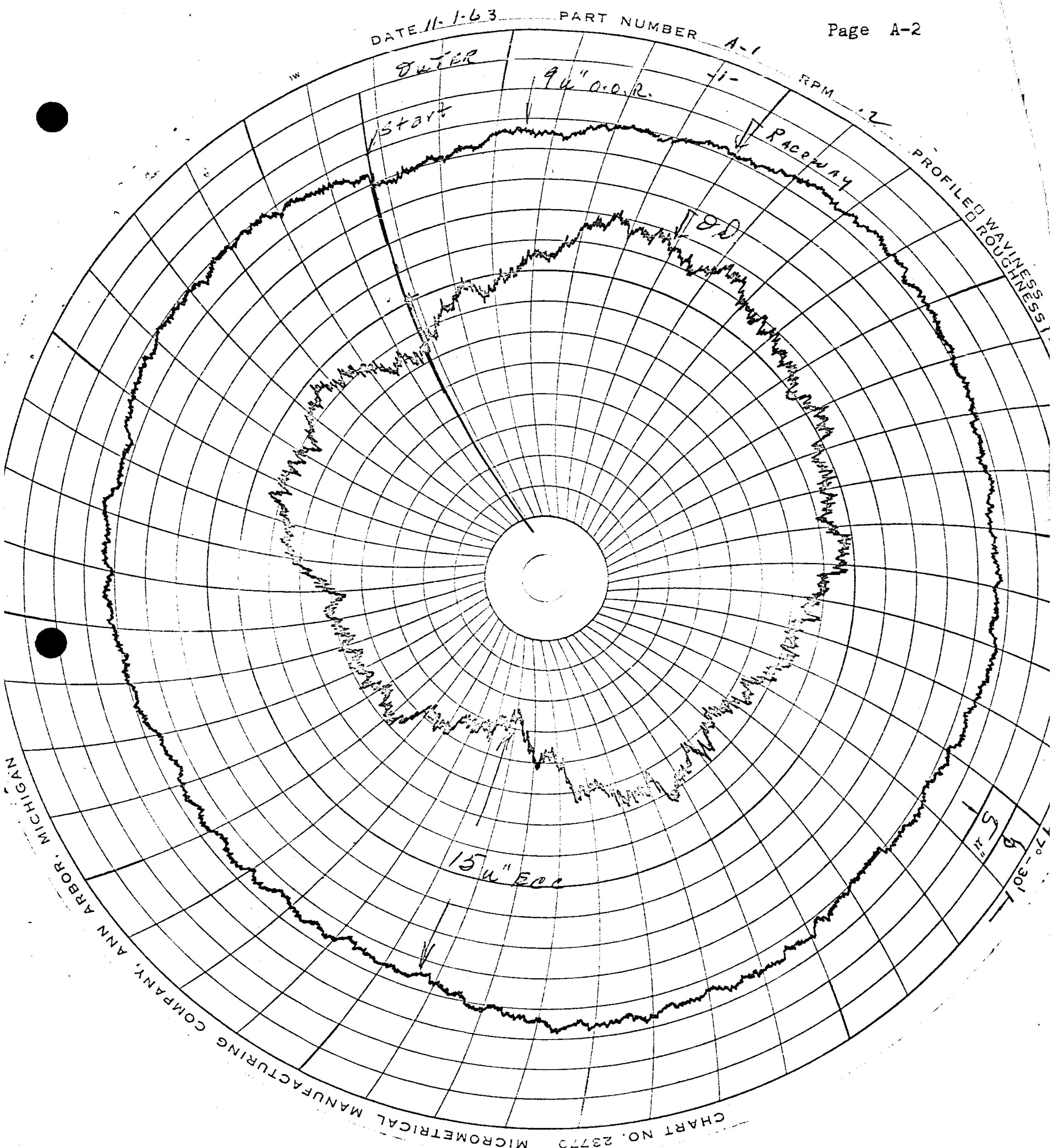

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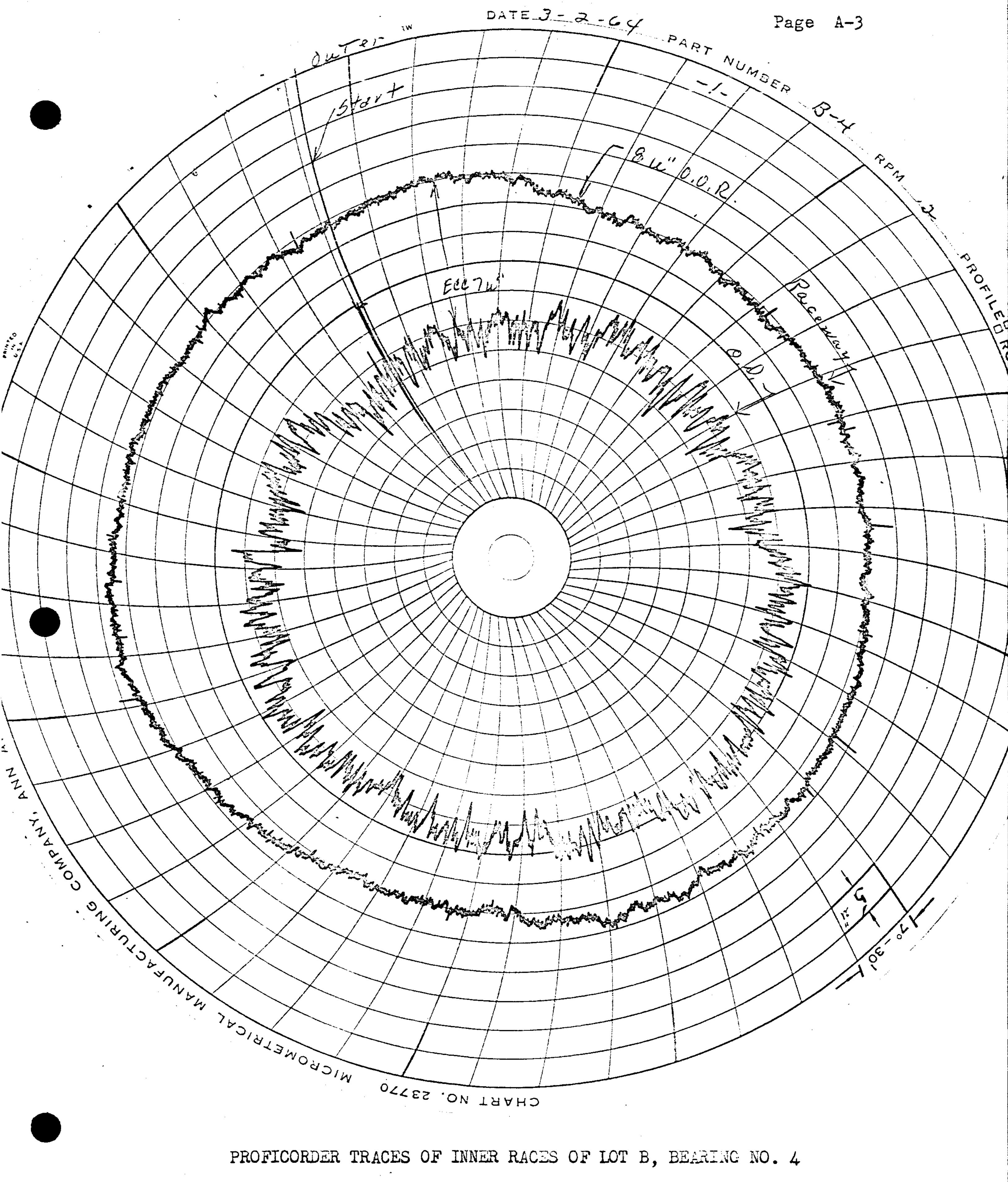

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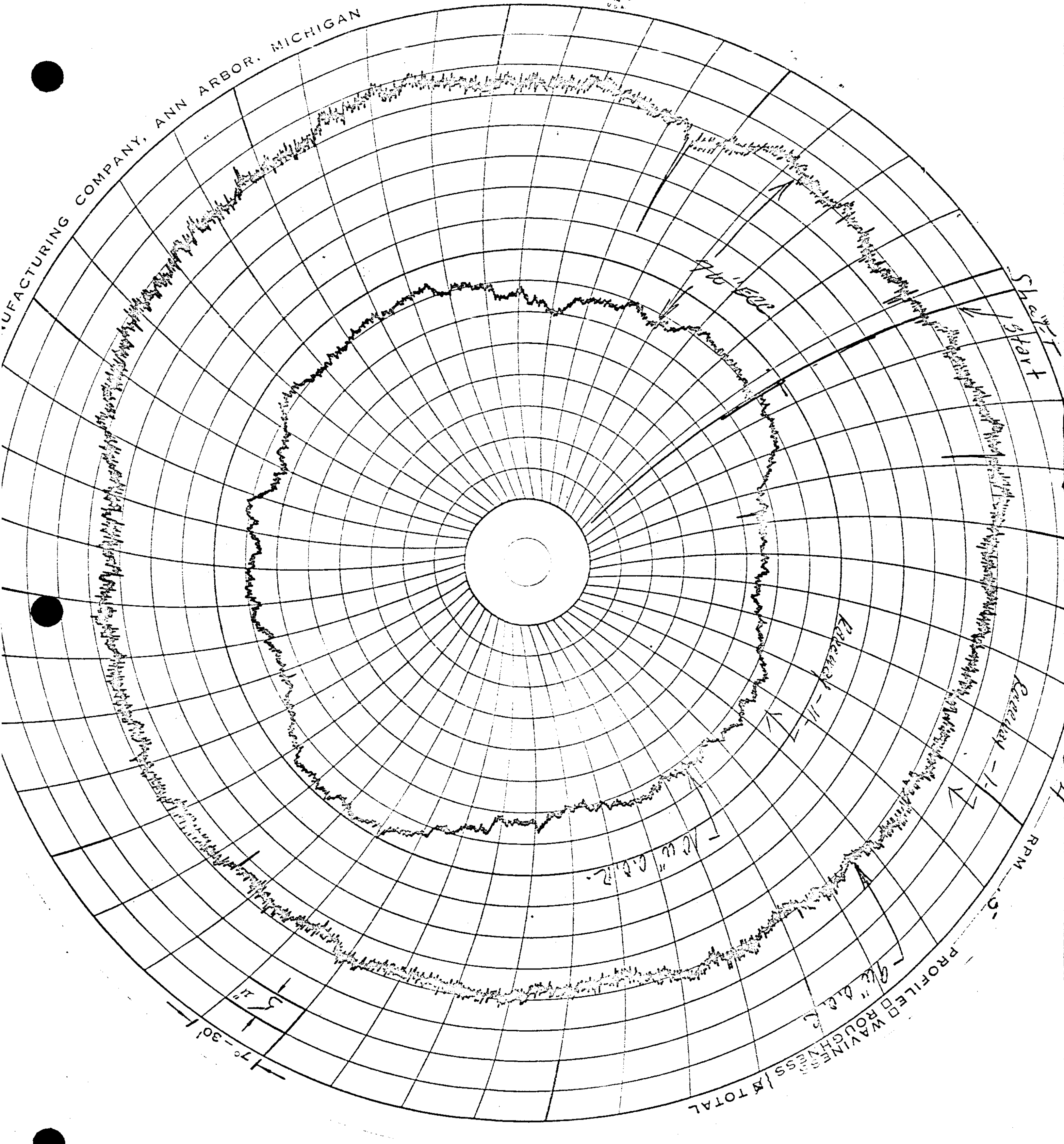

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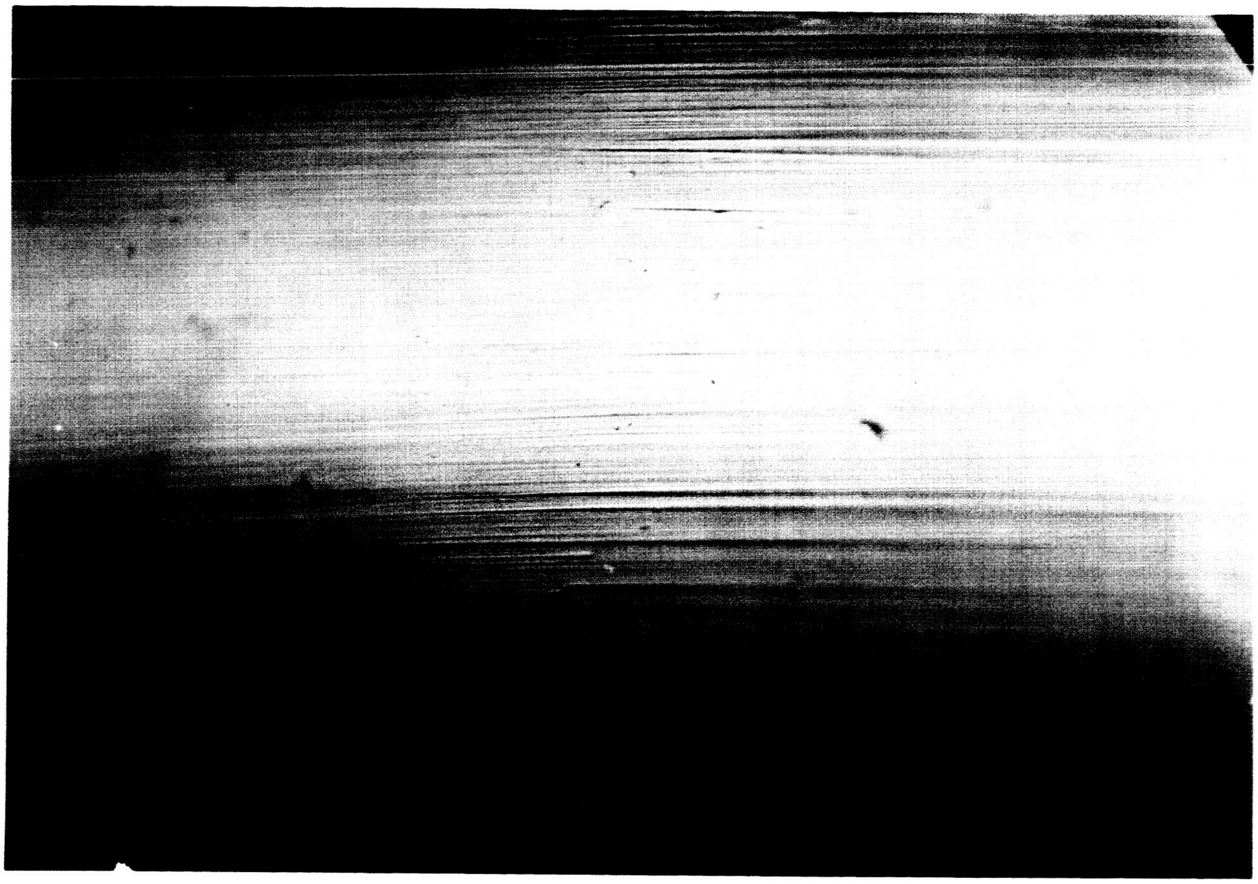

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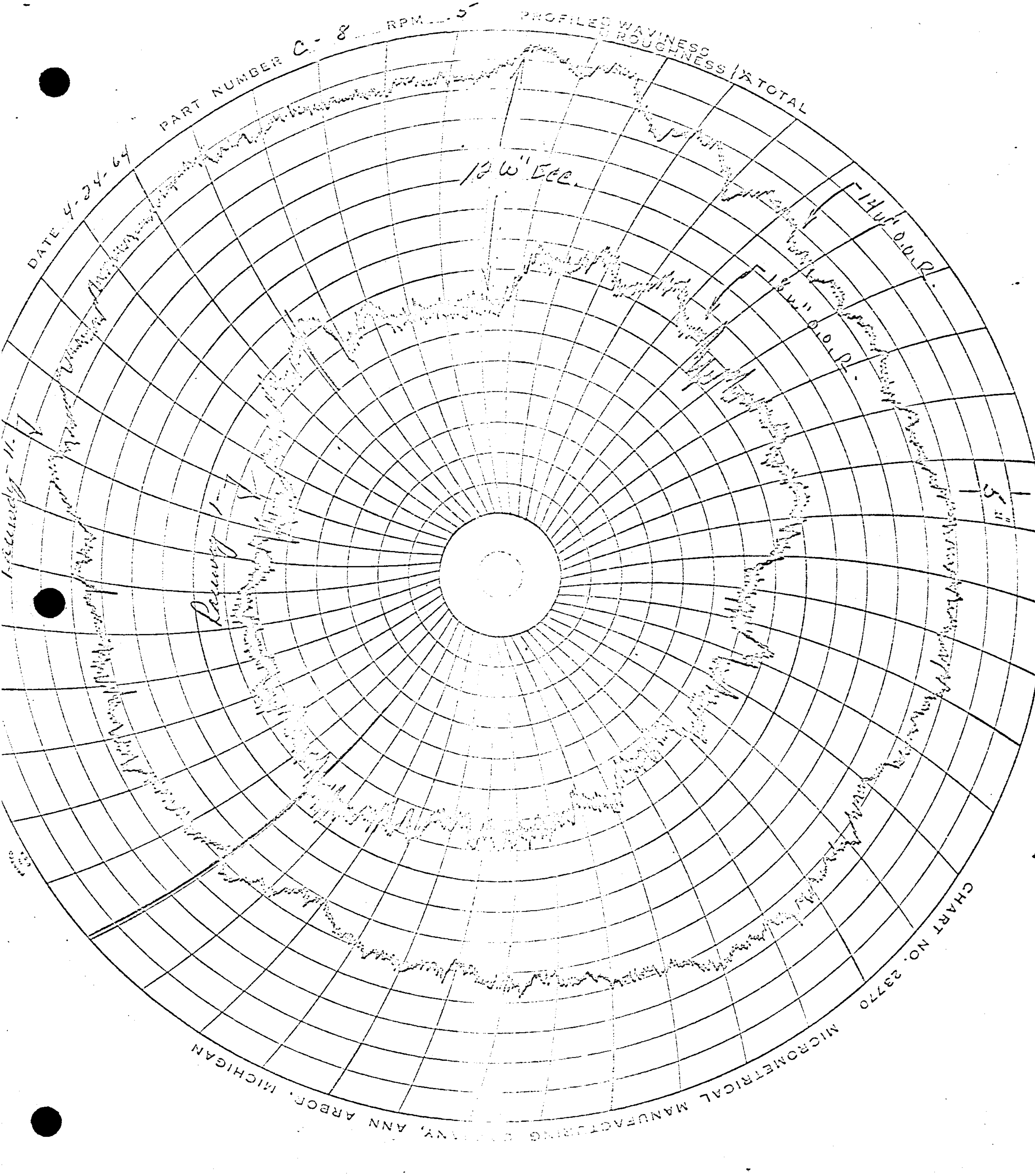

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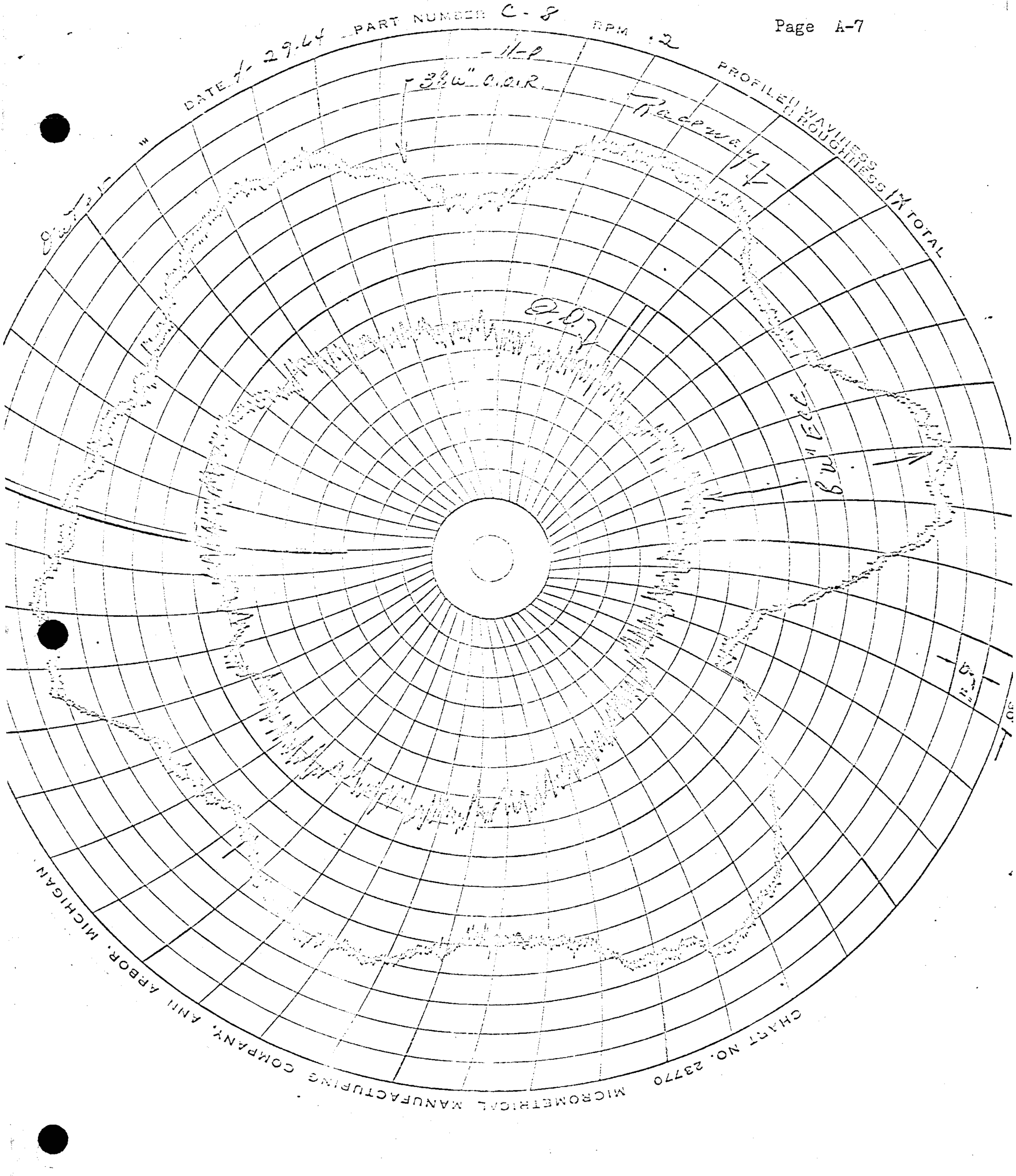

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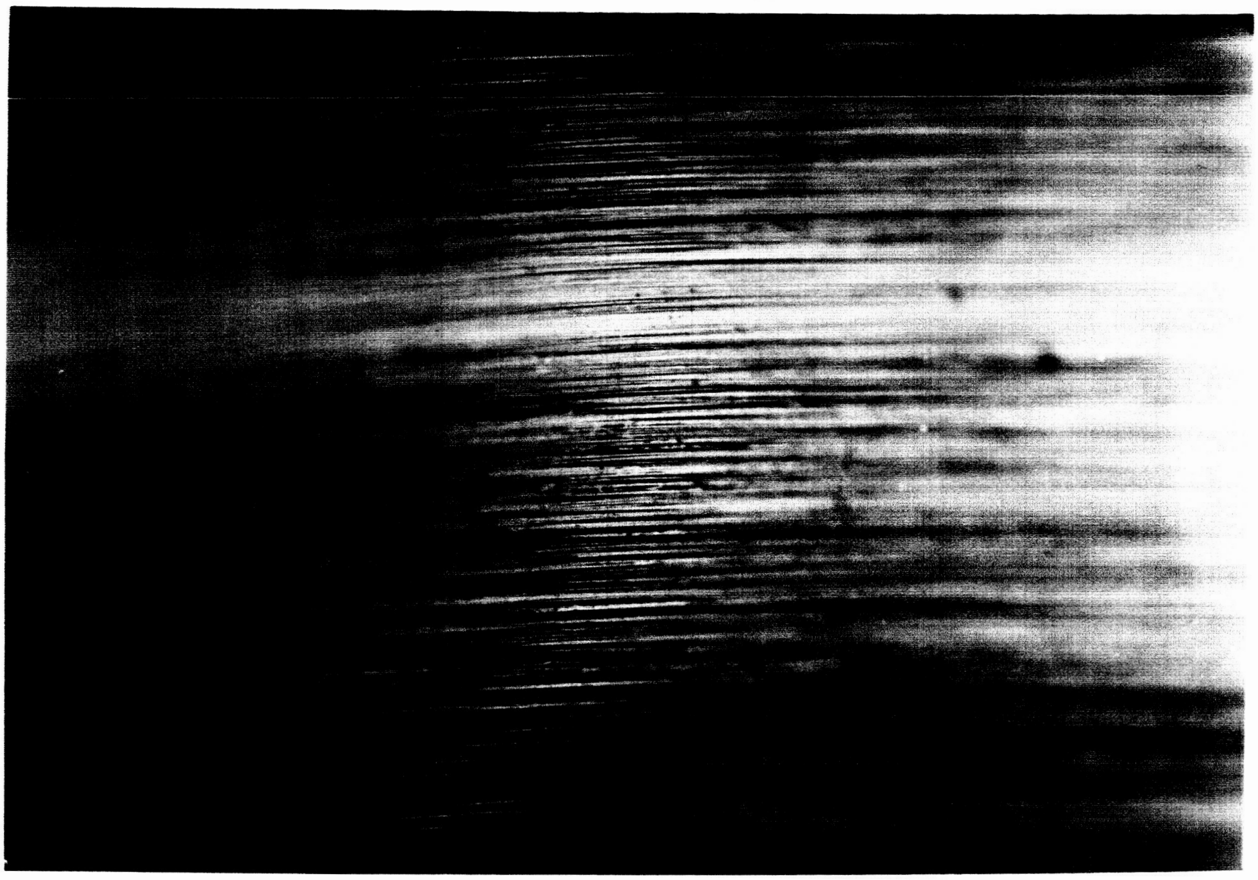

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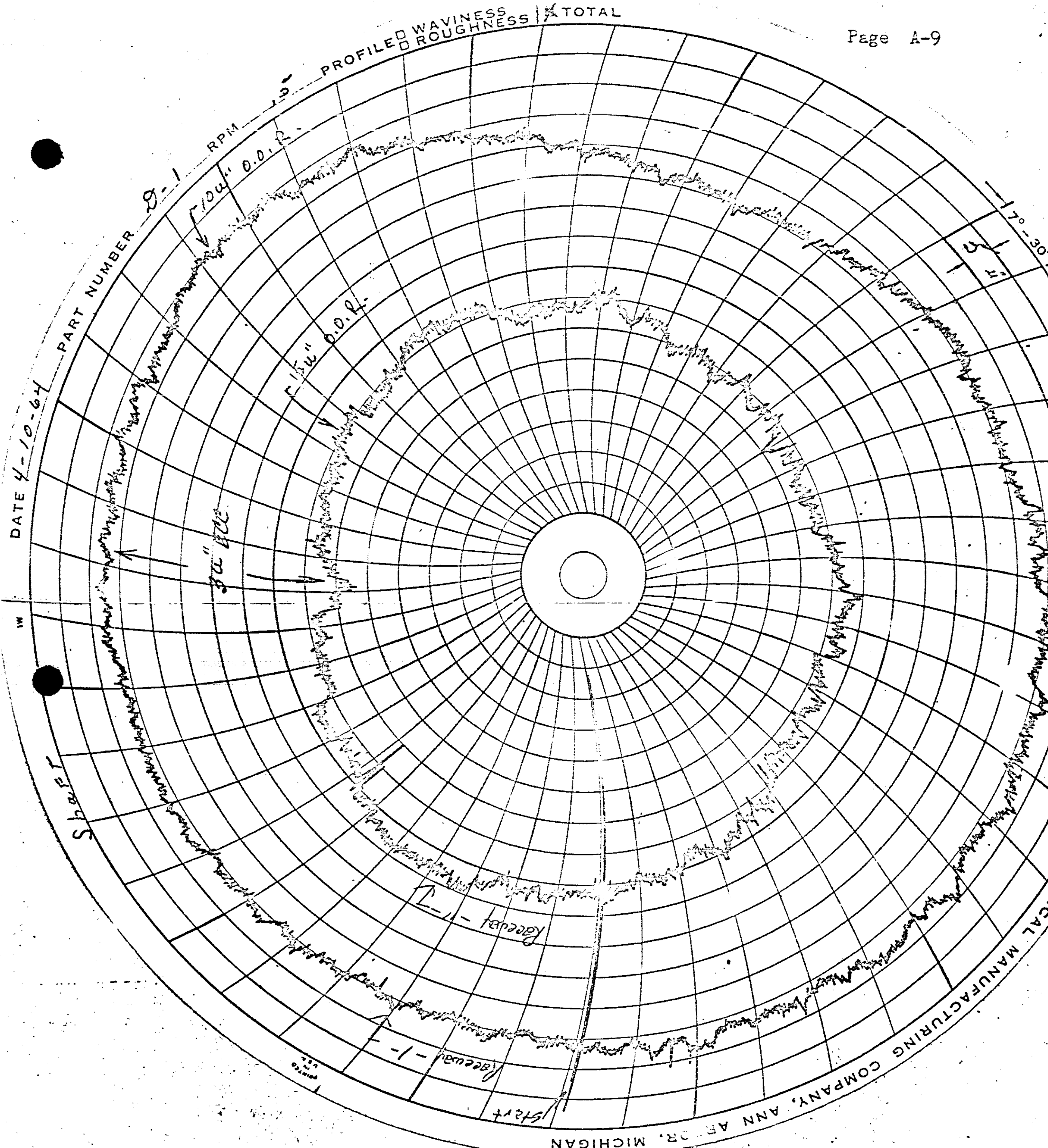

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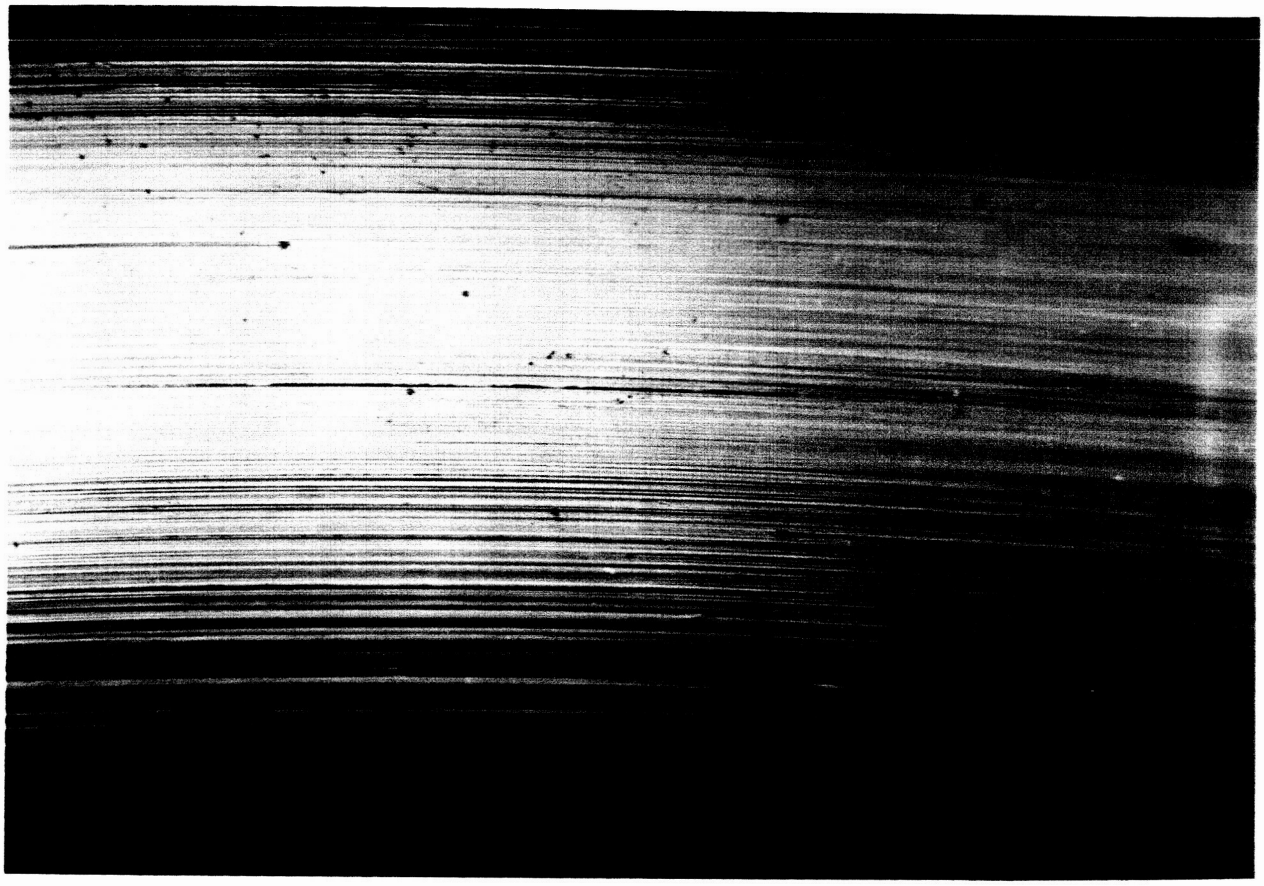

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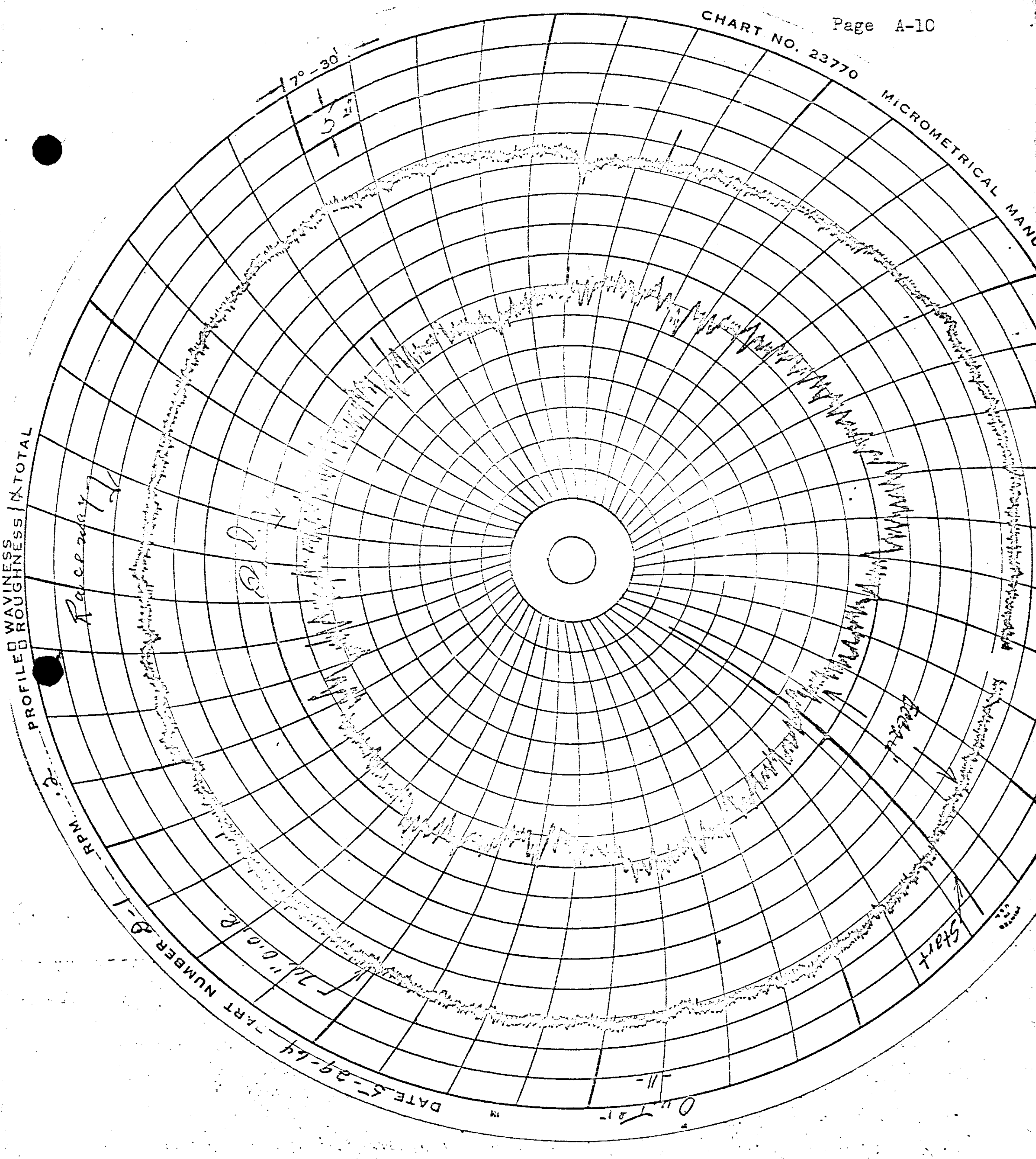

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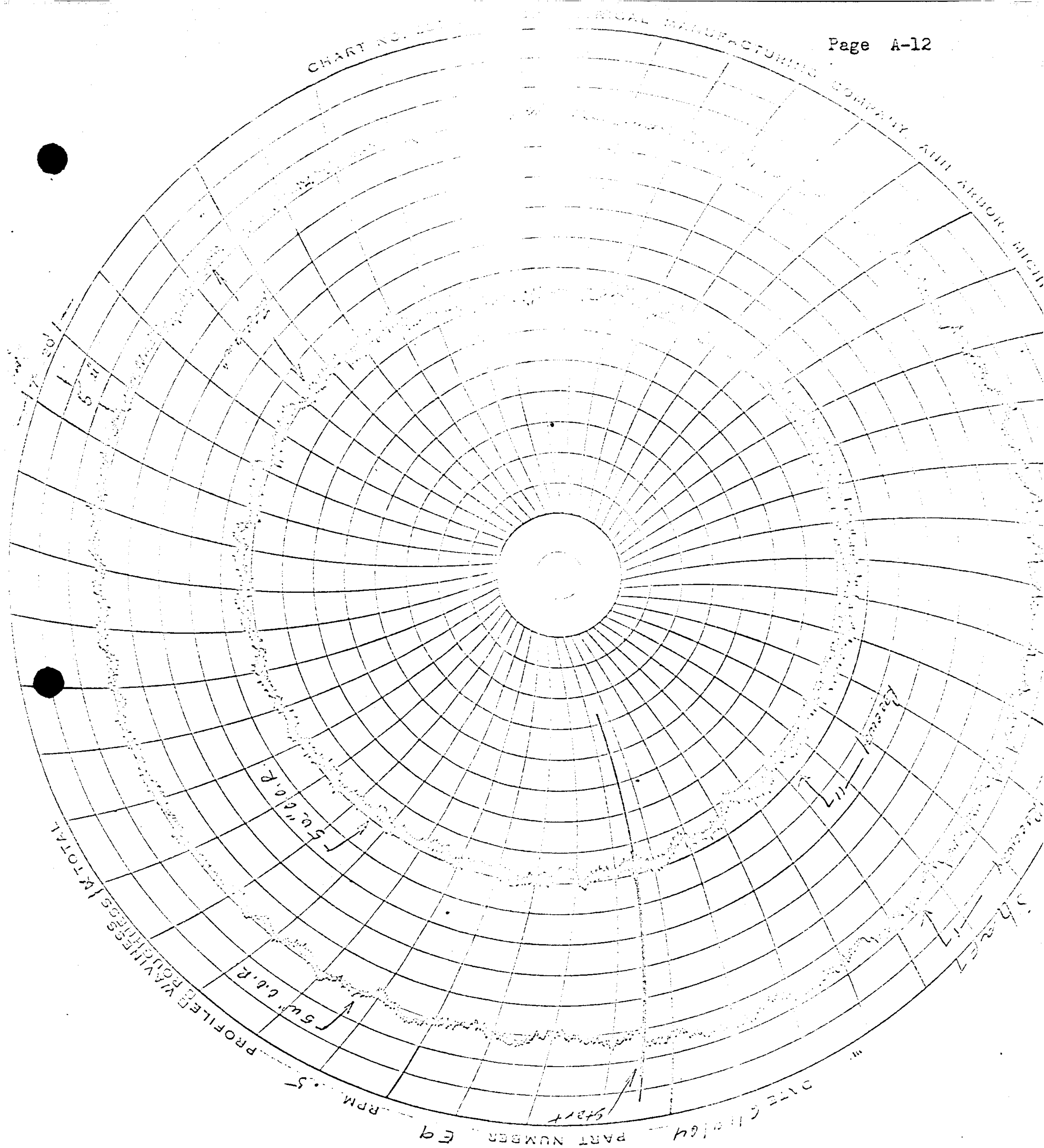

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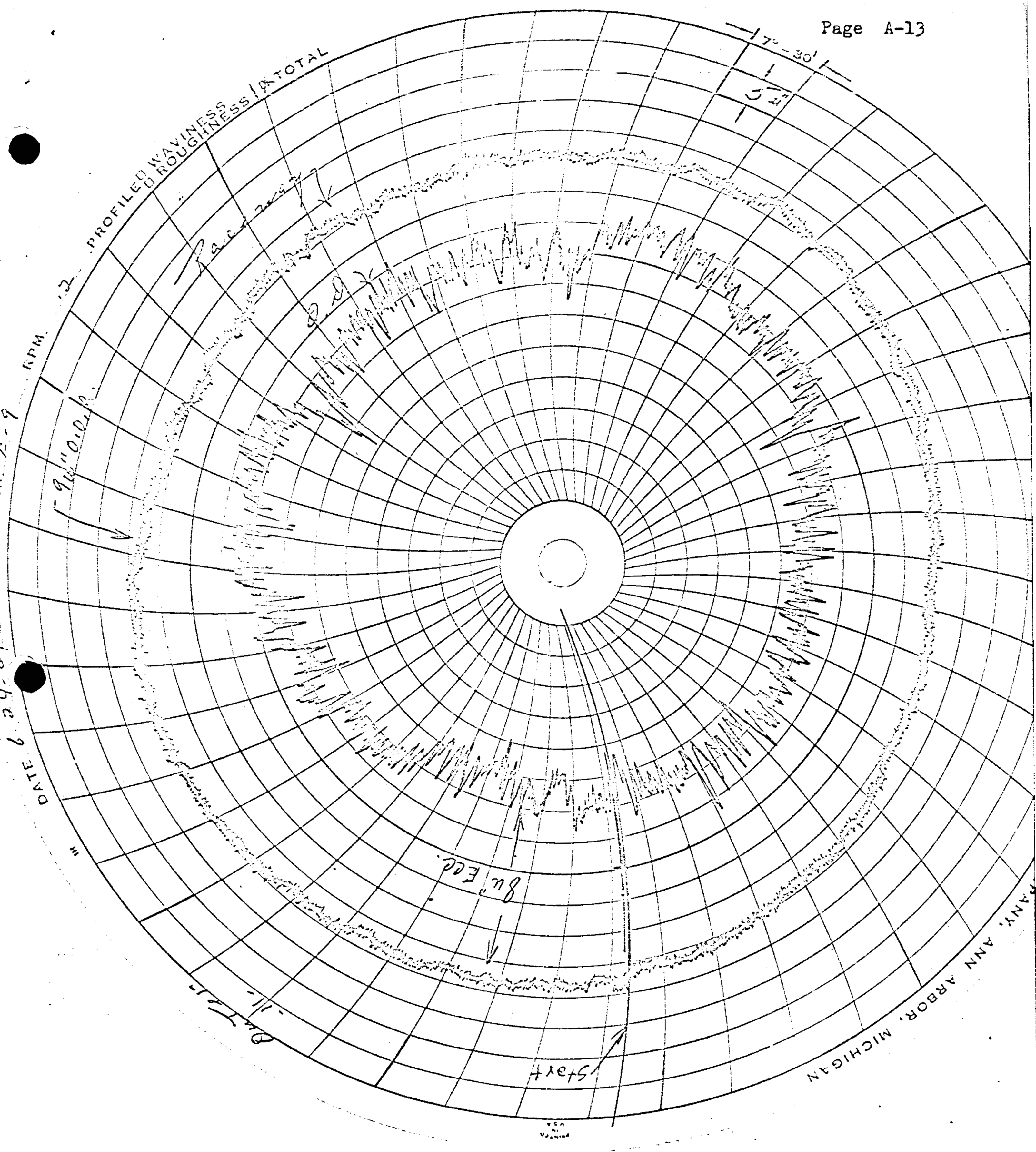

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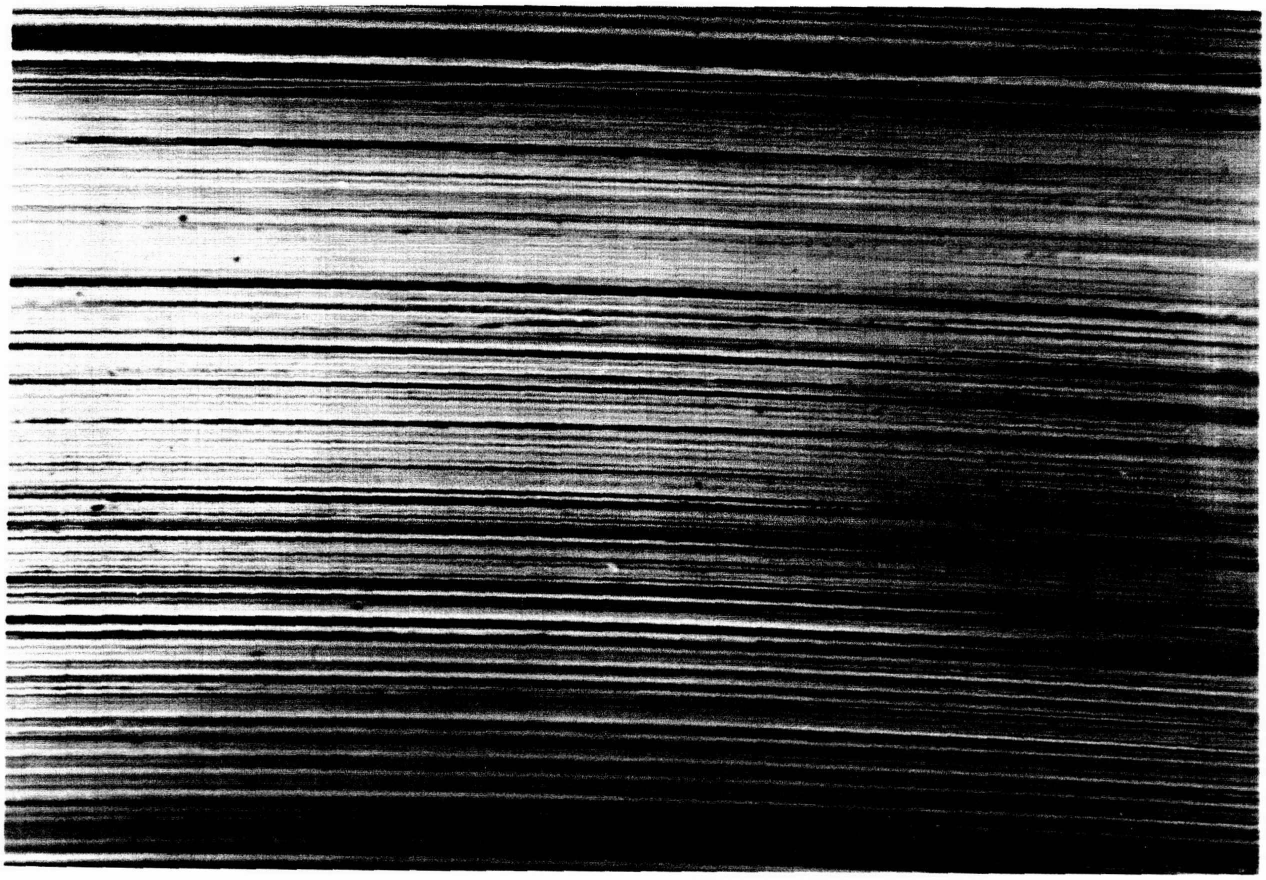

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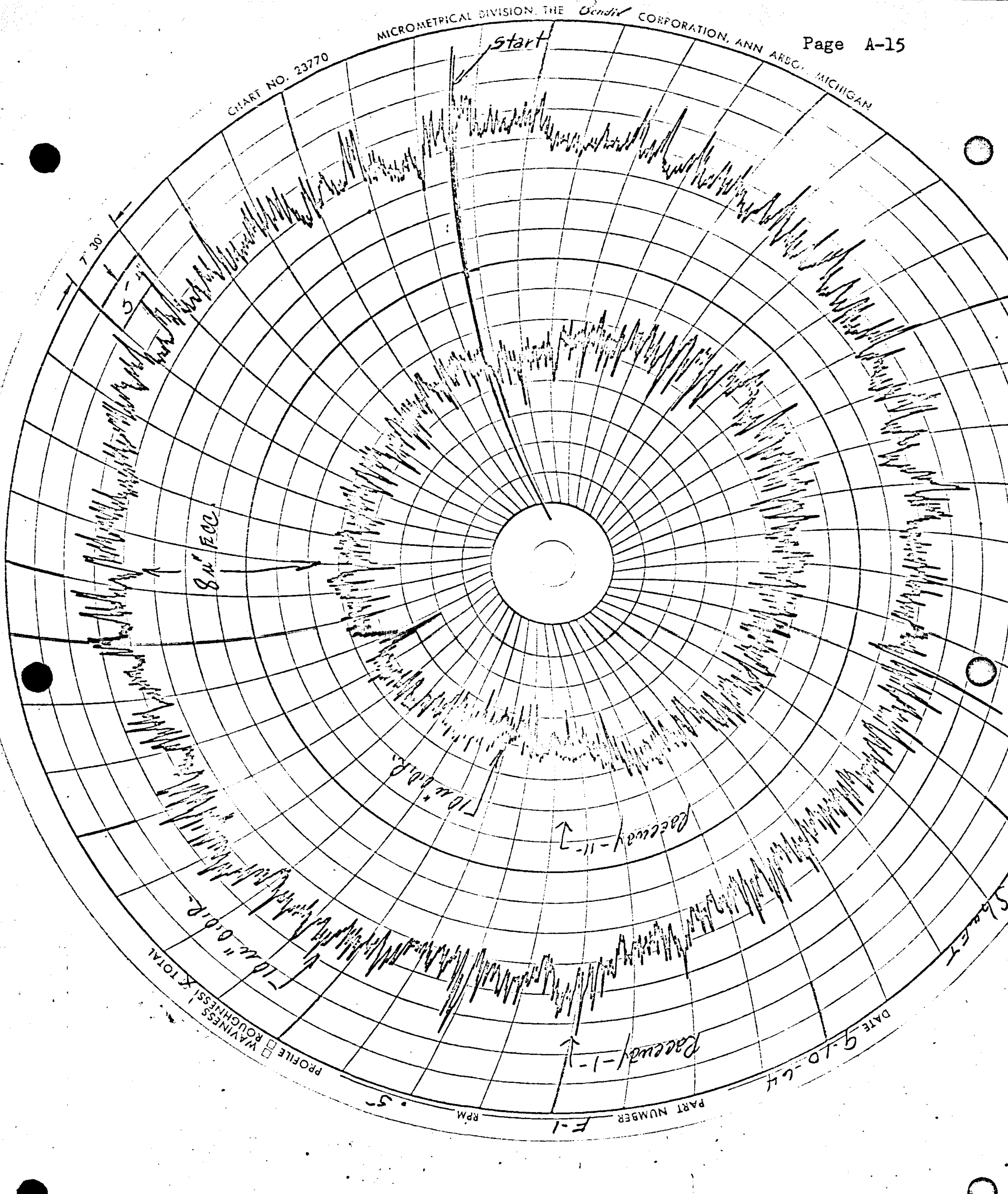

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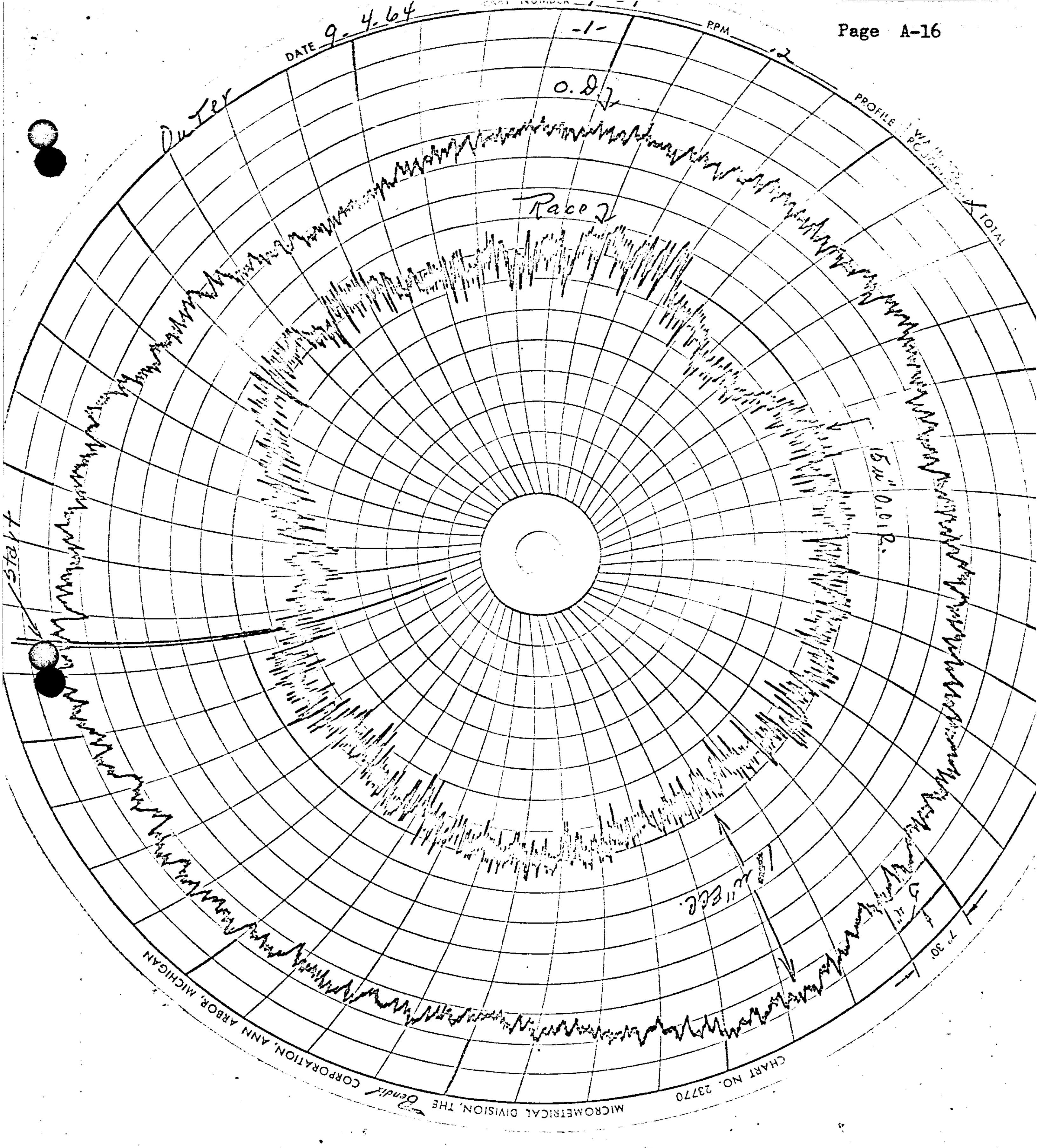

PROFICORDER TRACES OF AN OUTER RACE AND OF O.D. OF OUTER OF LOT F, BEARING NO. 1

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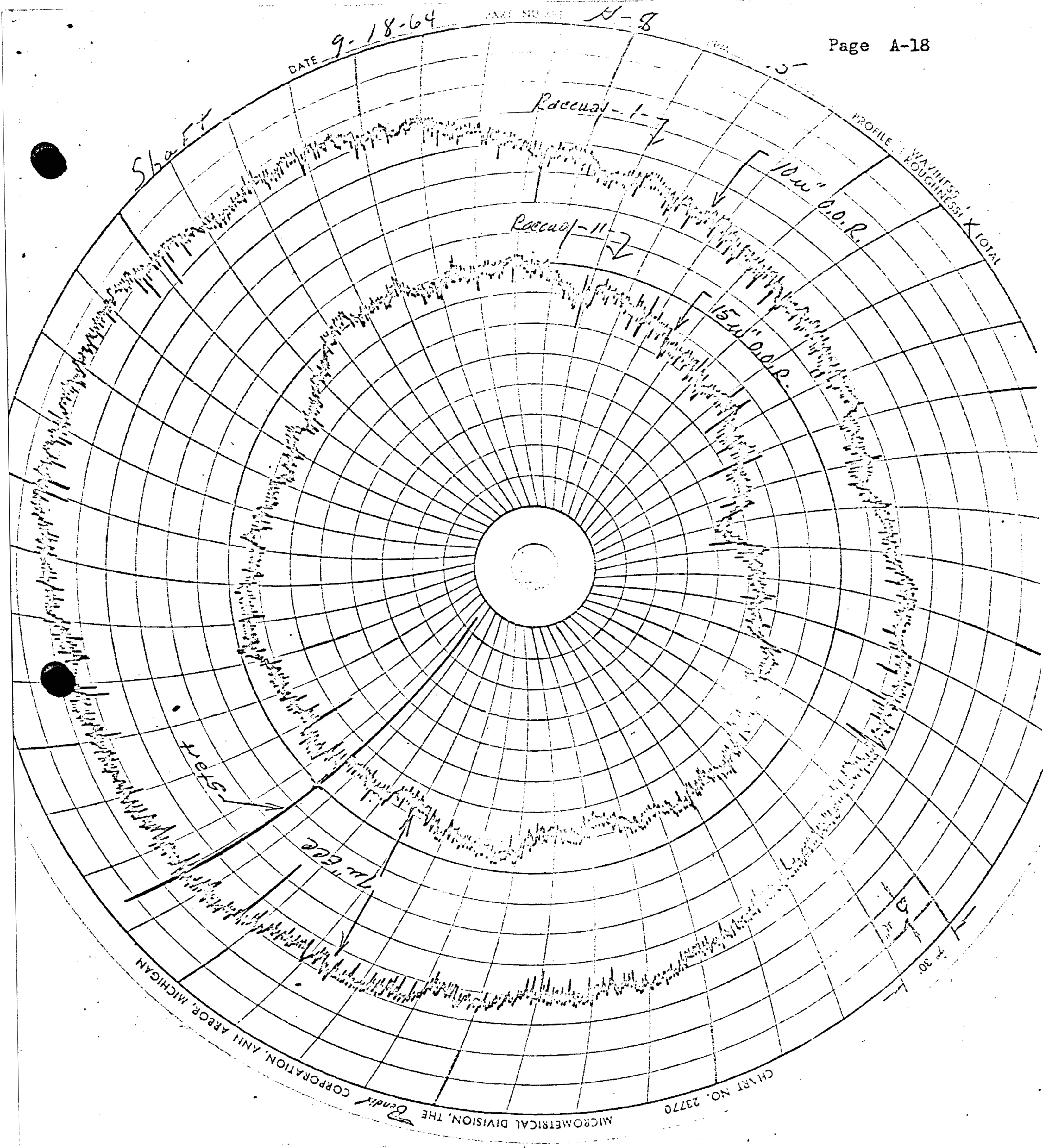

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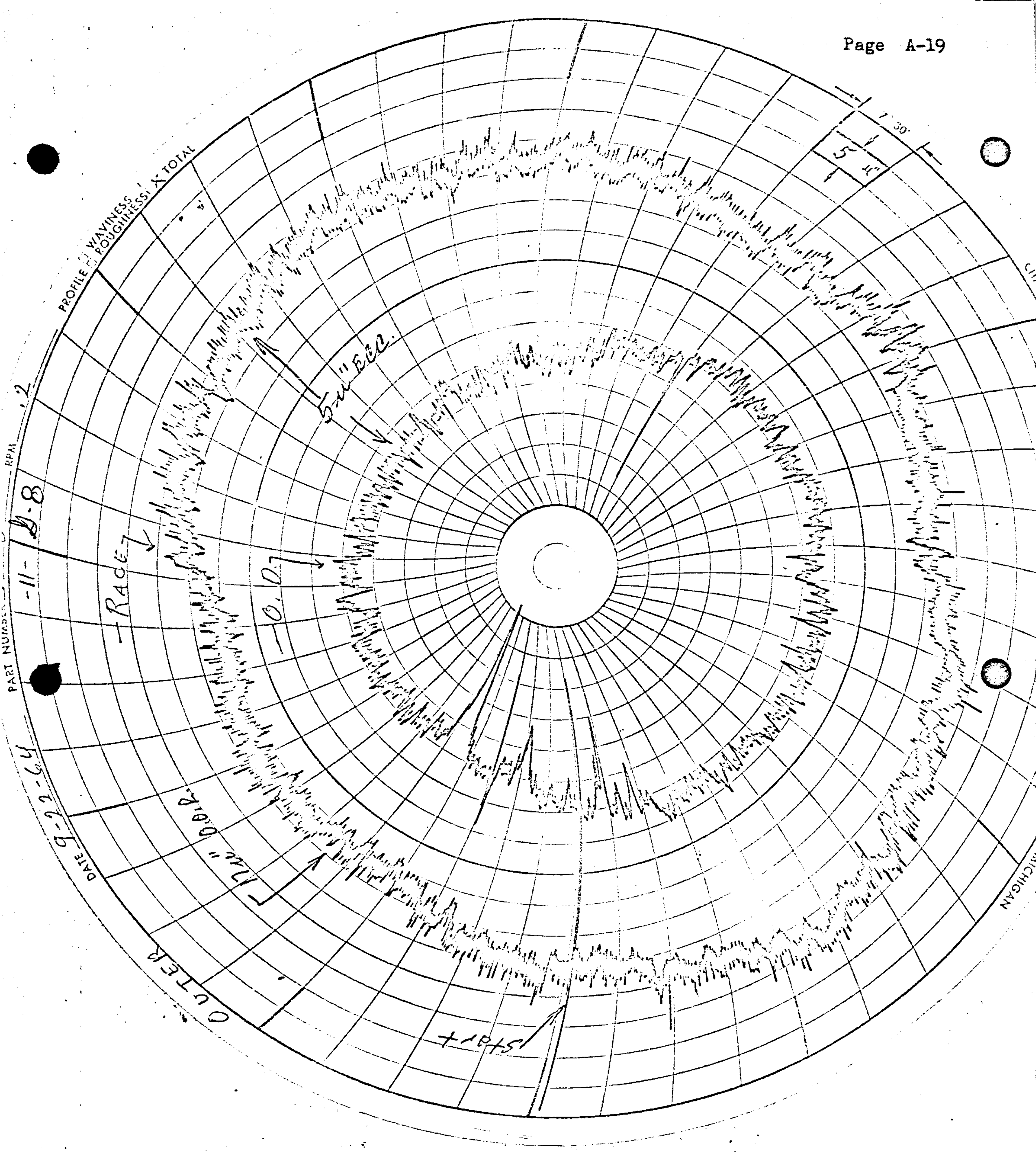

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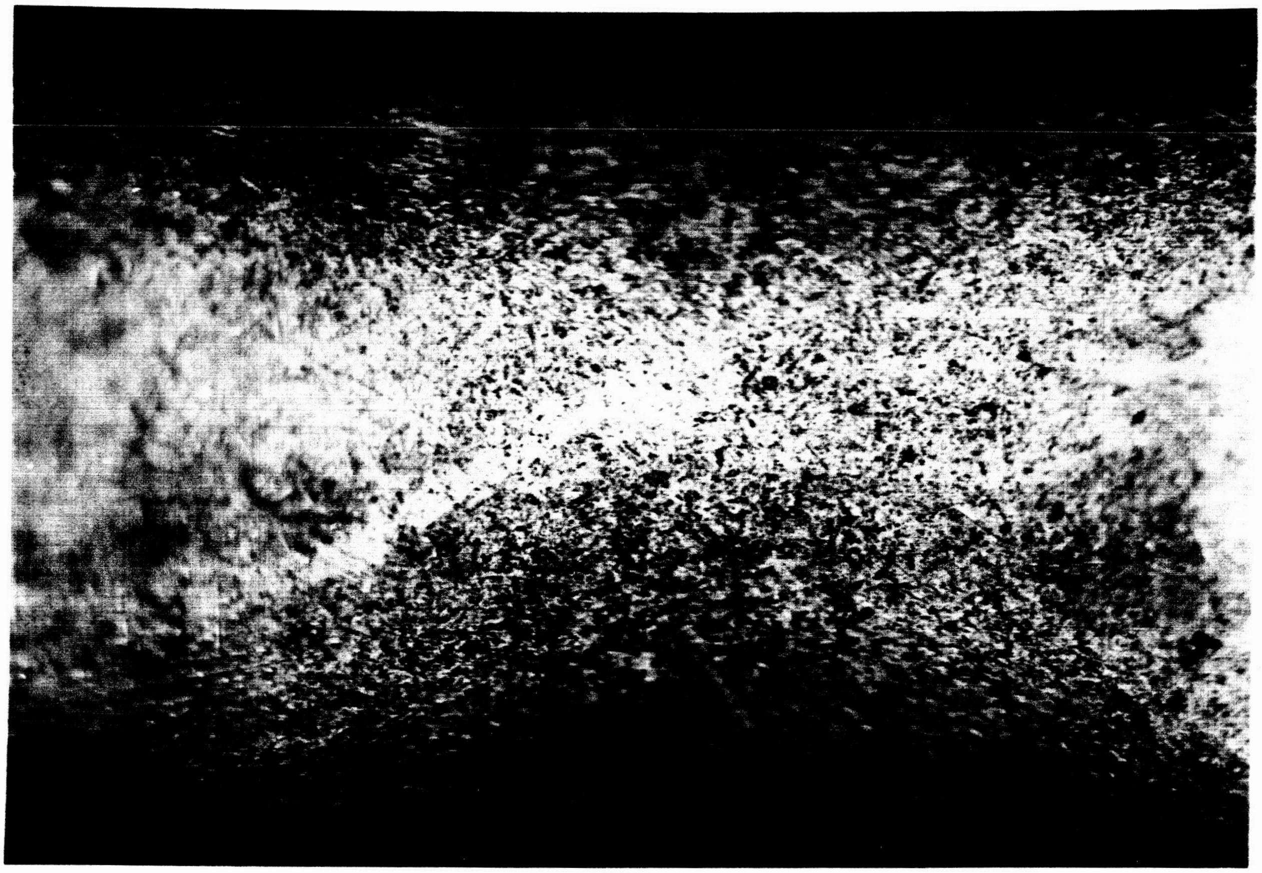

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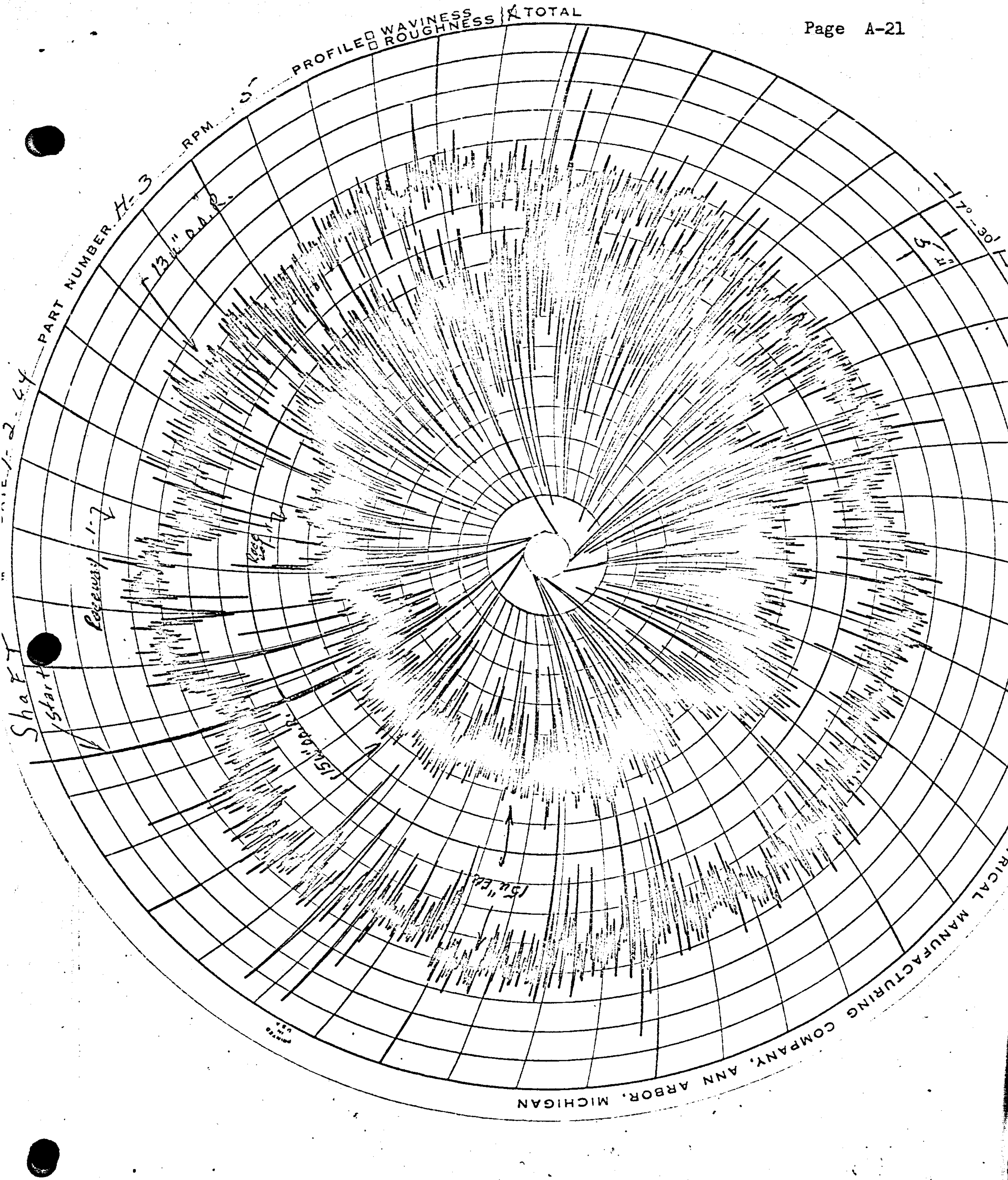

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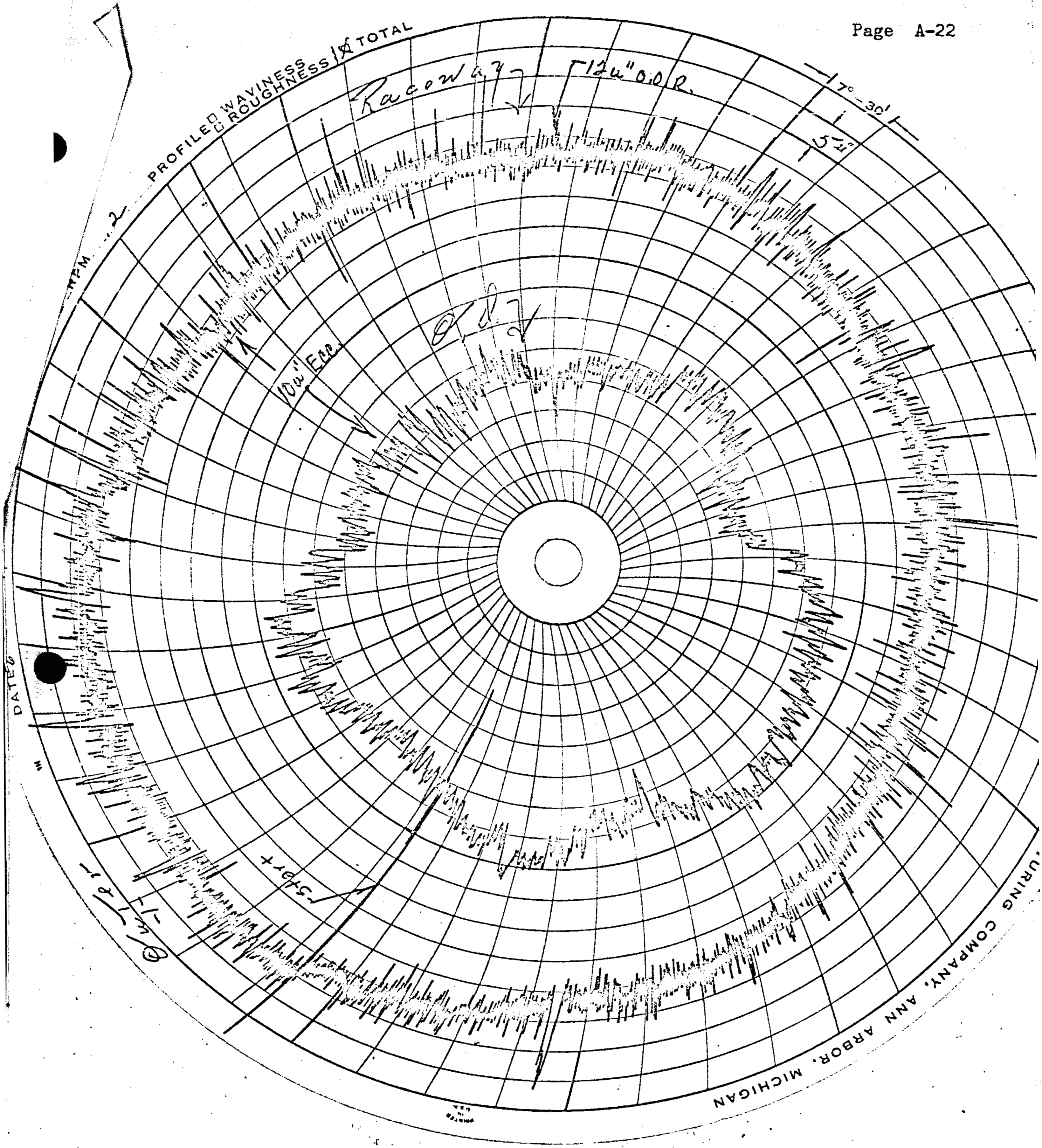

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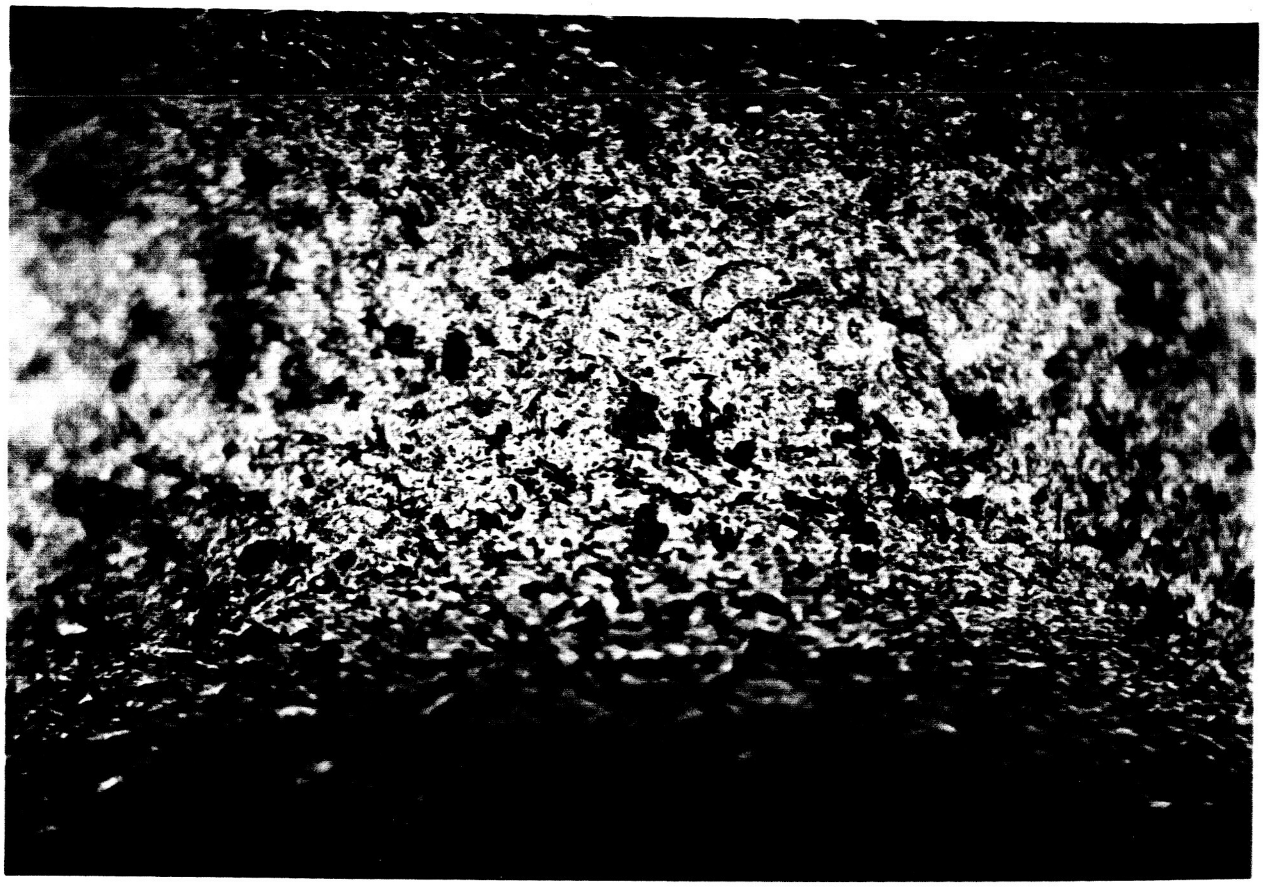

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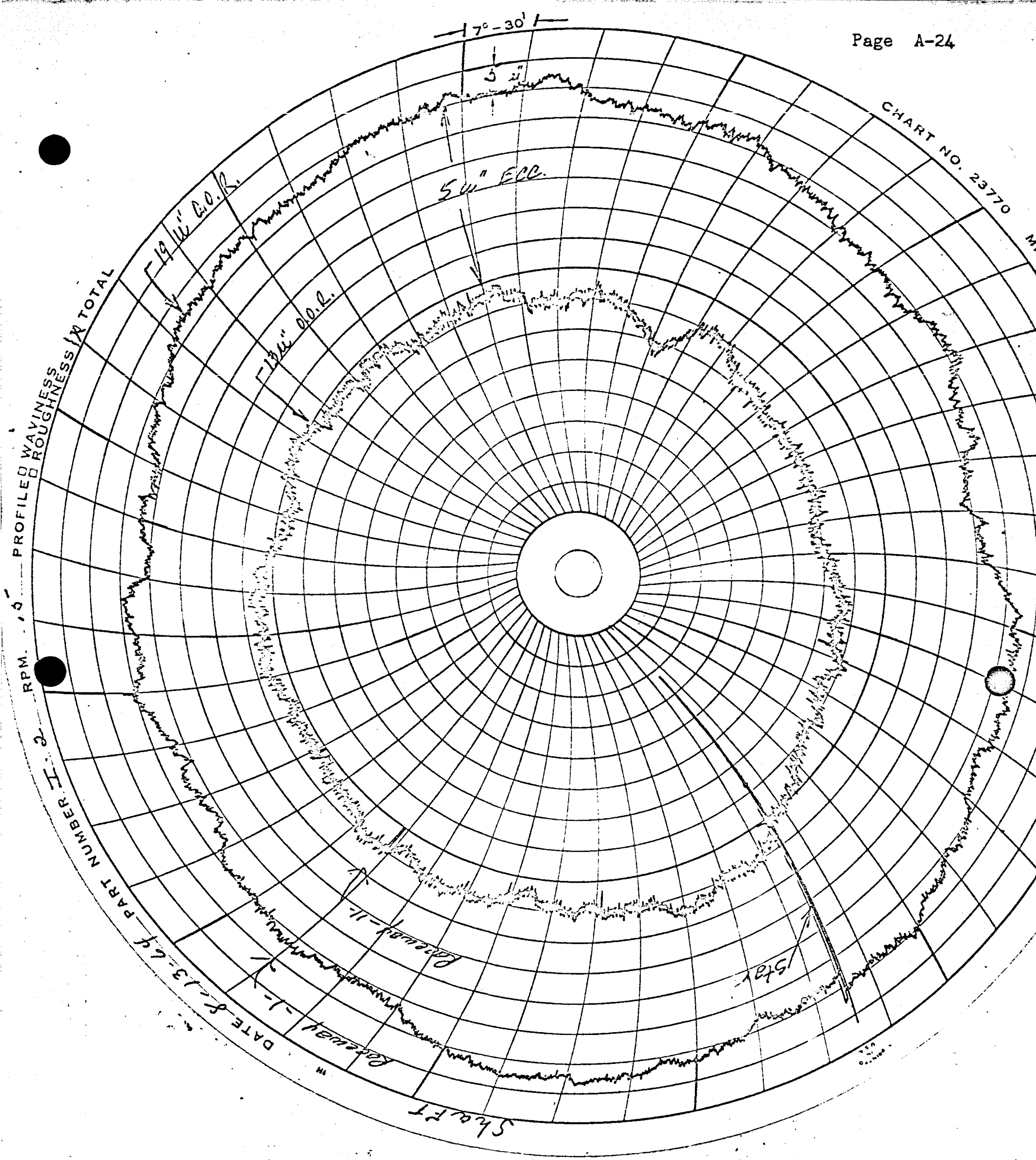

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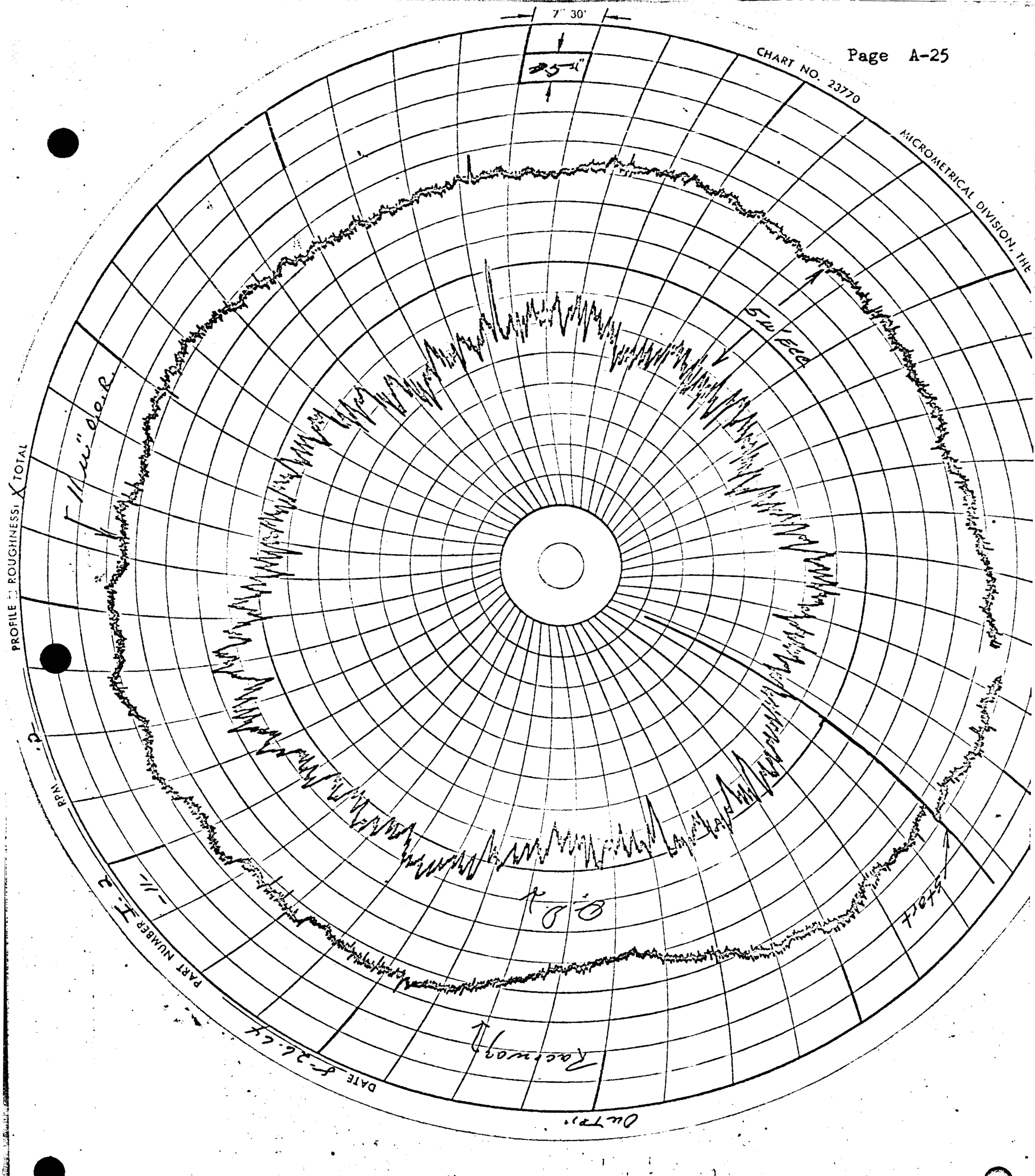

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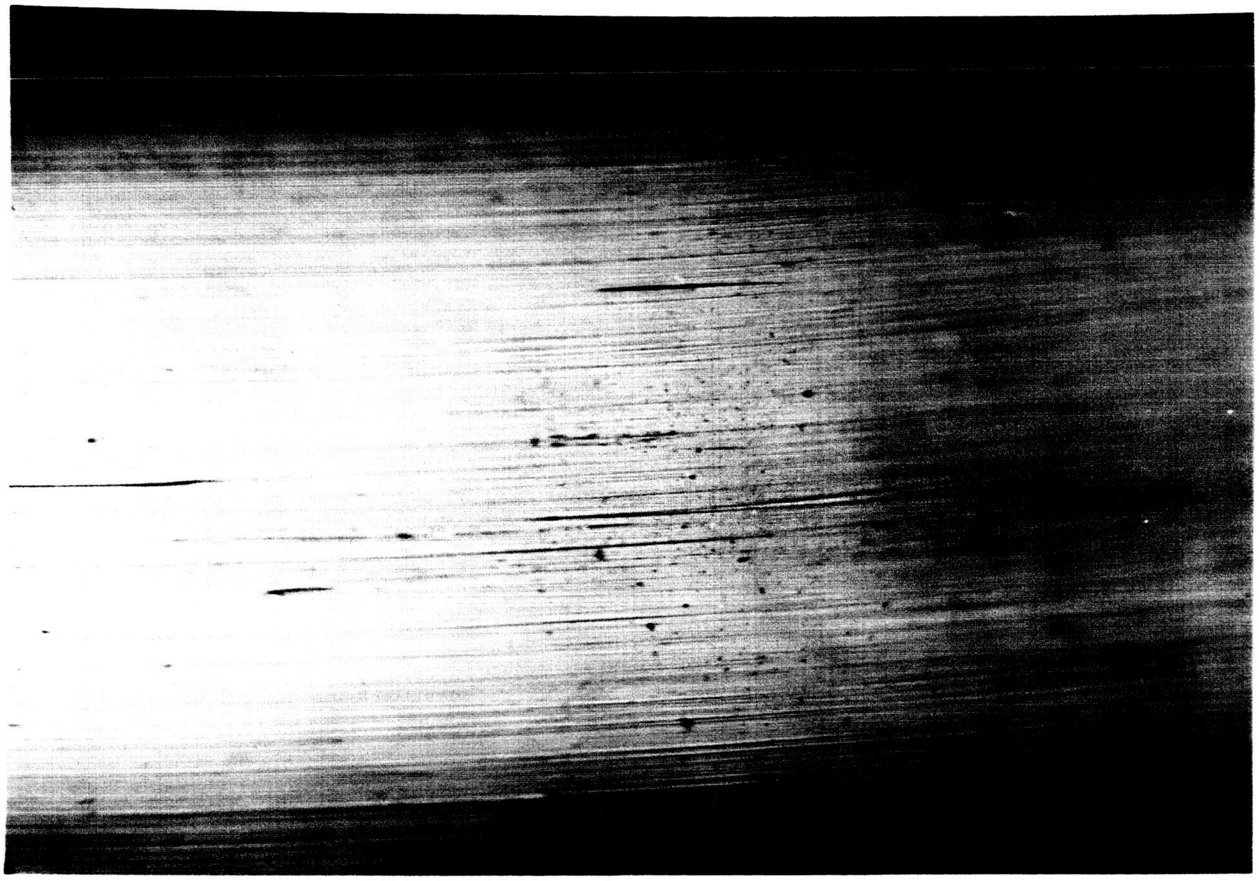

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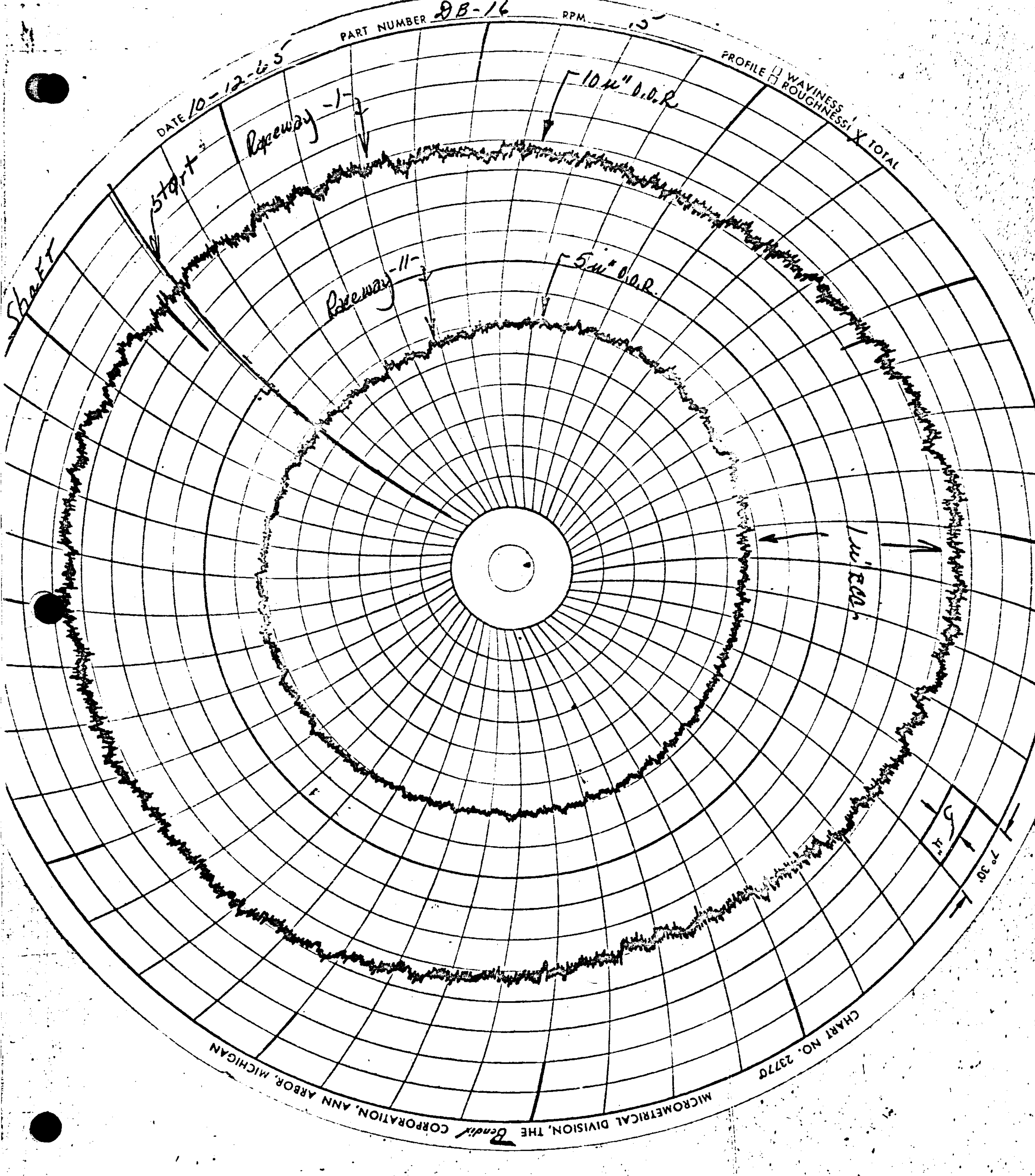

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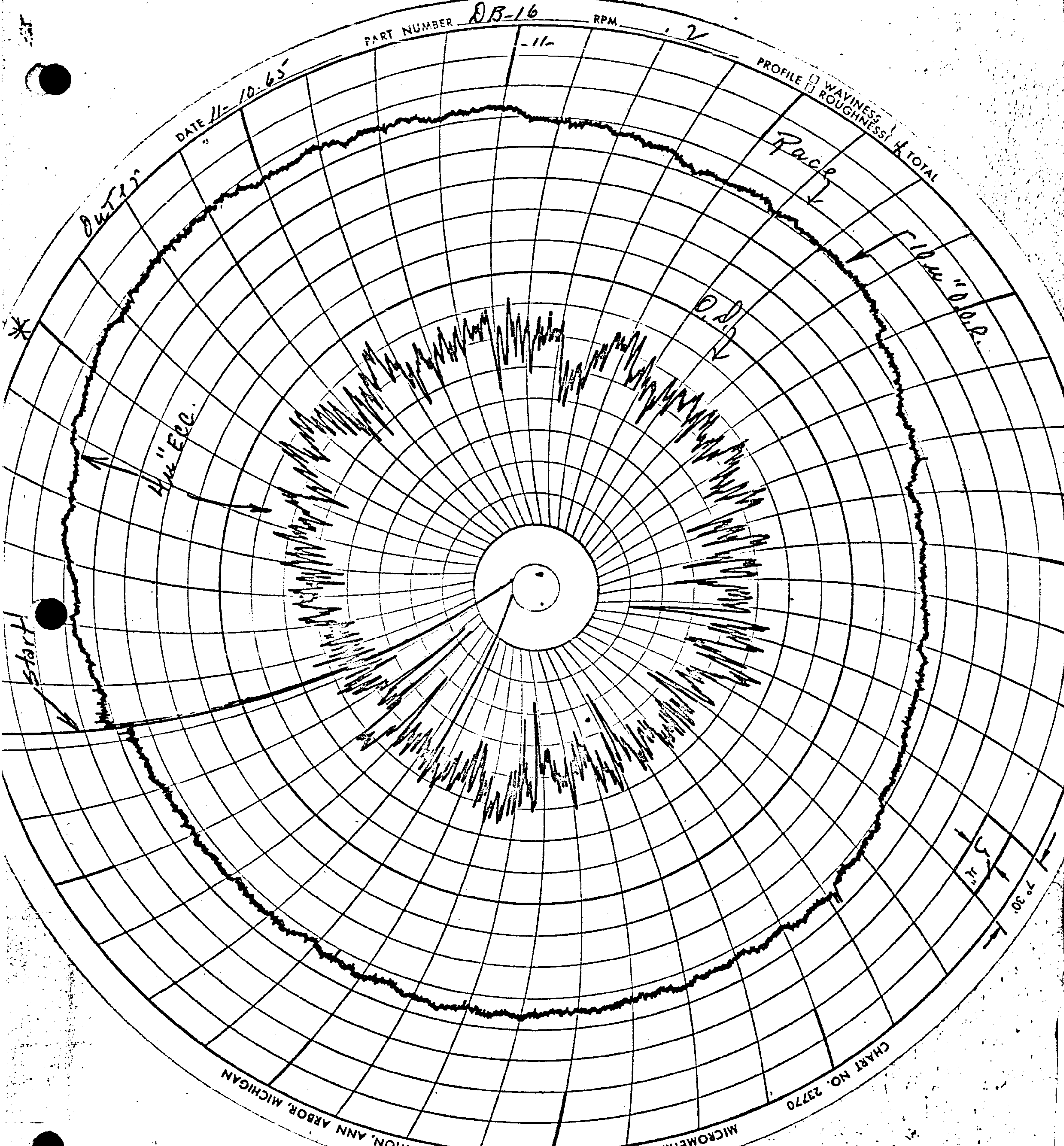

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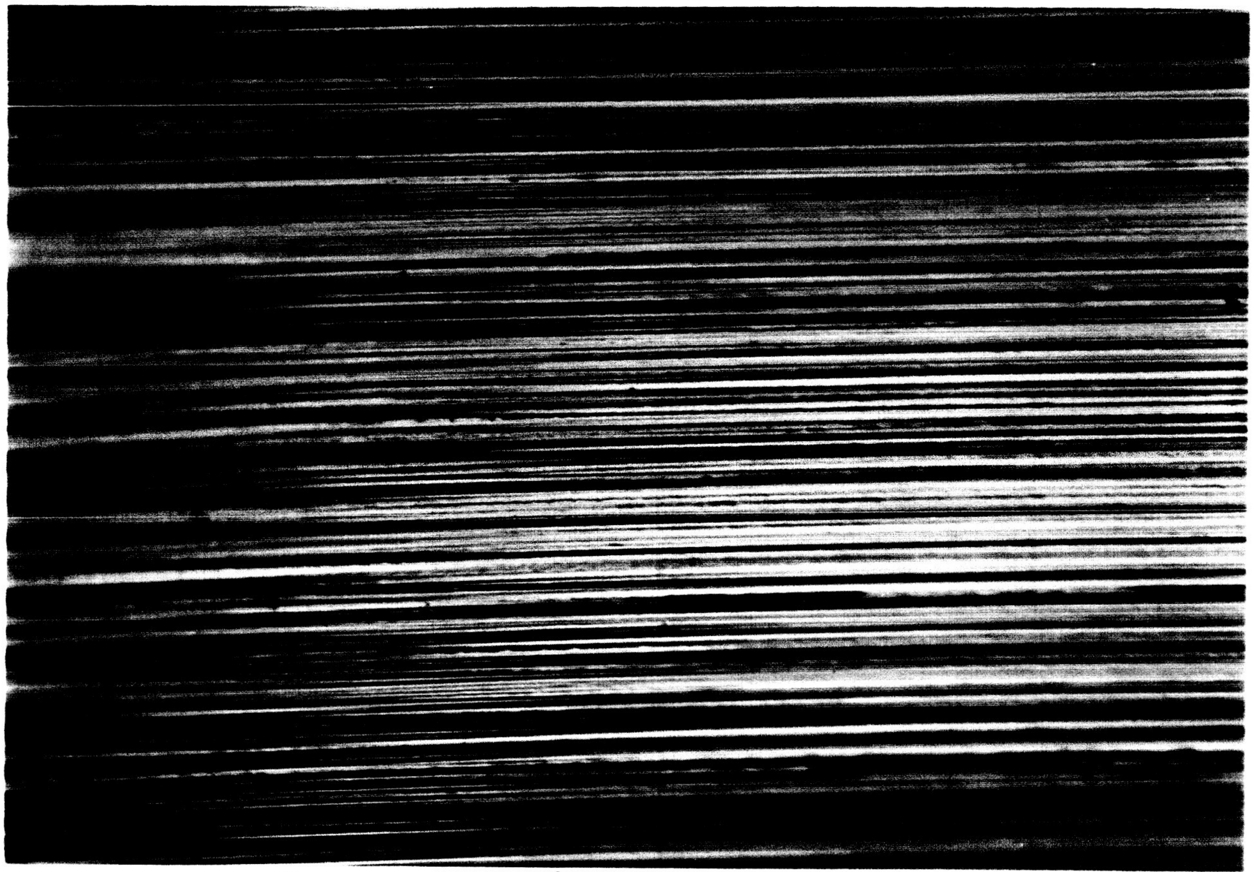
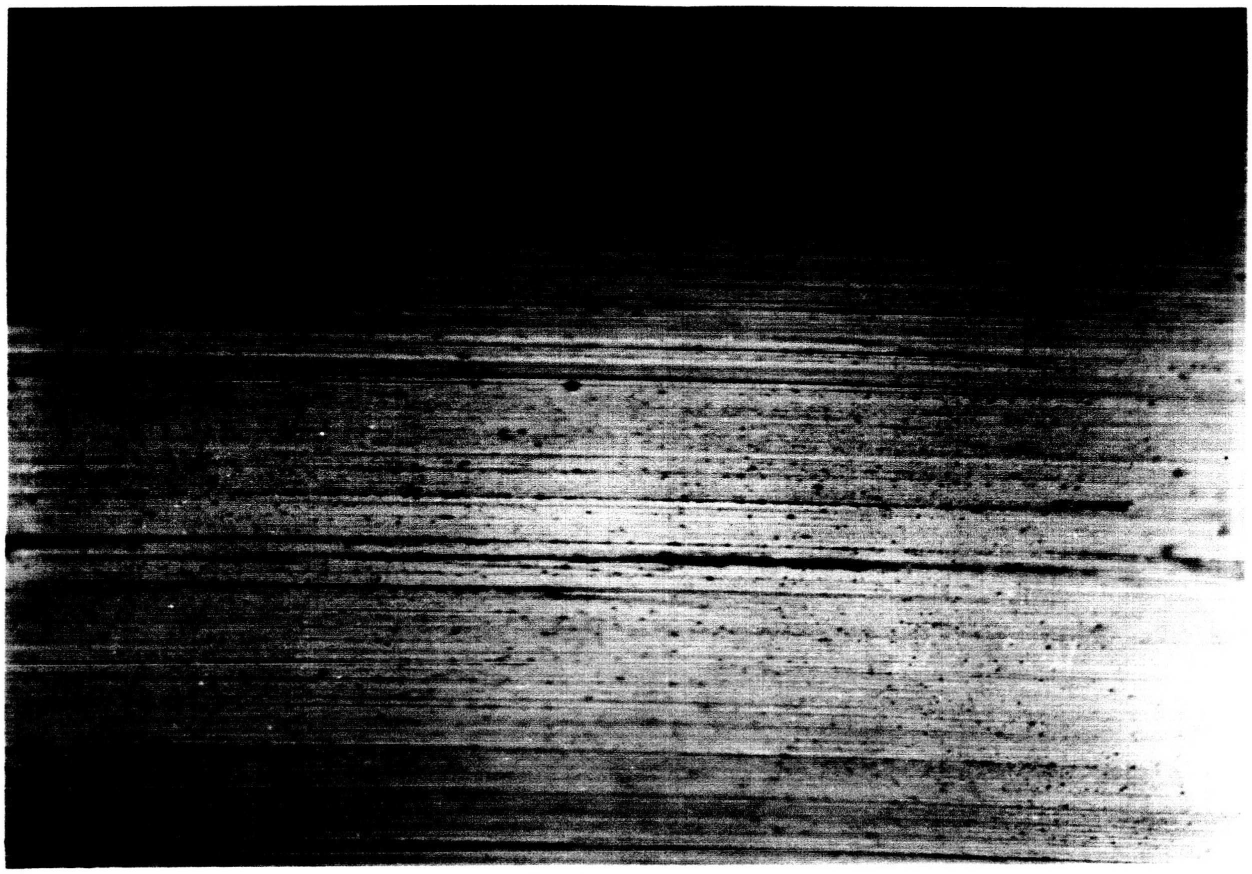
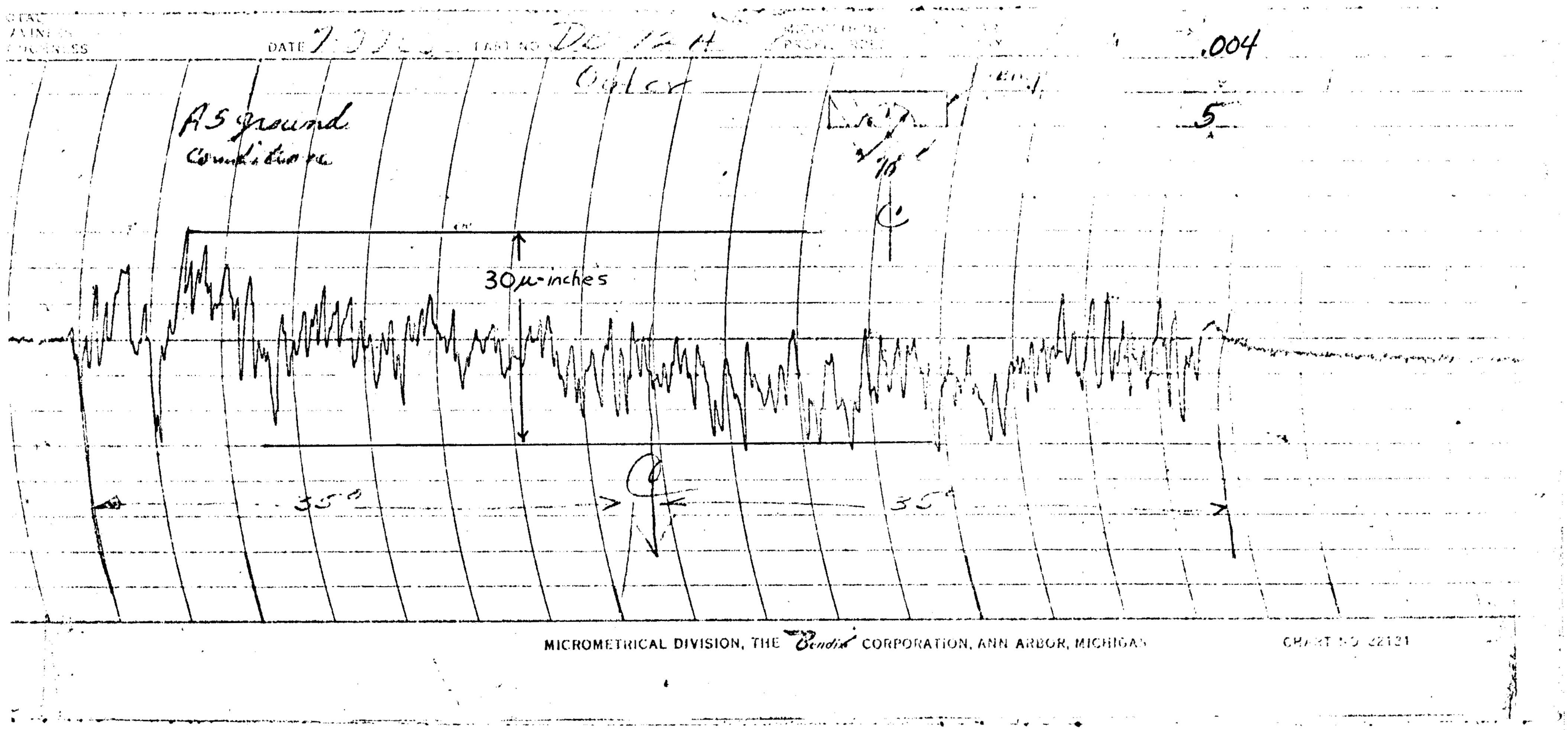


400X - D - Finish Shaft DB-1-1-side



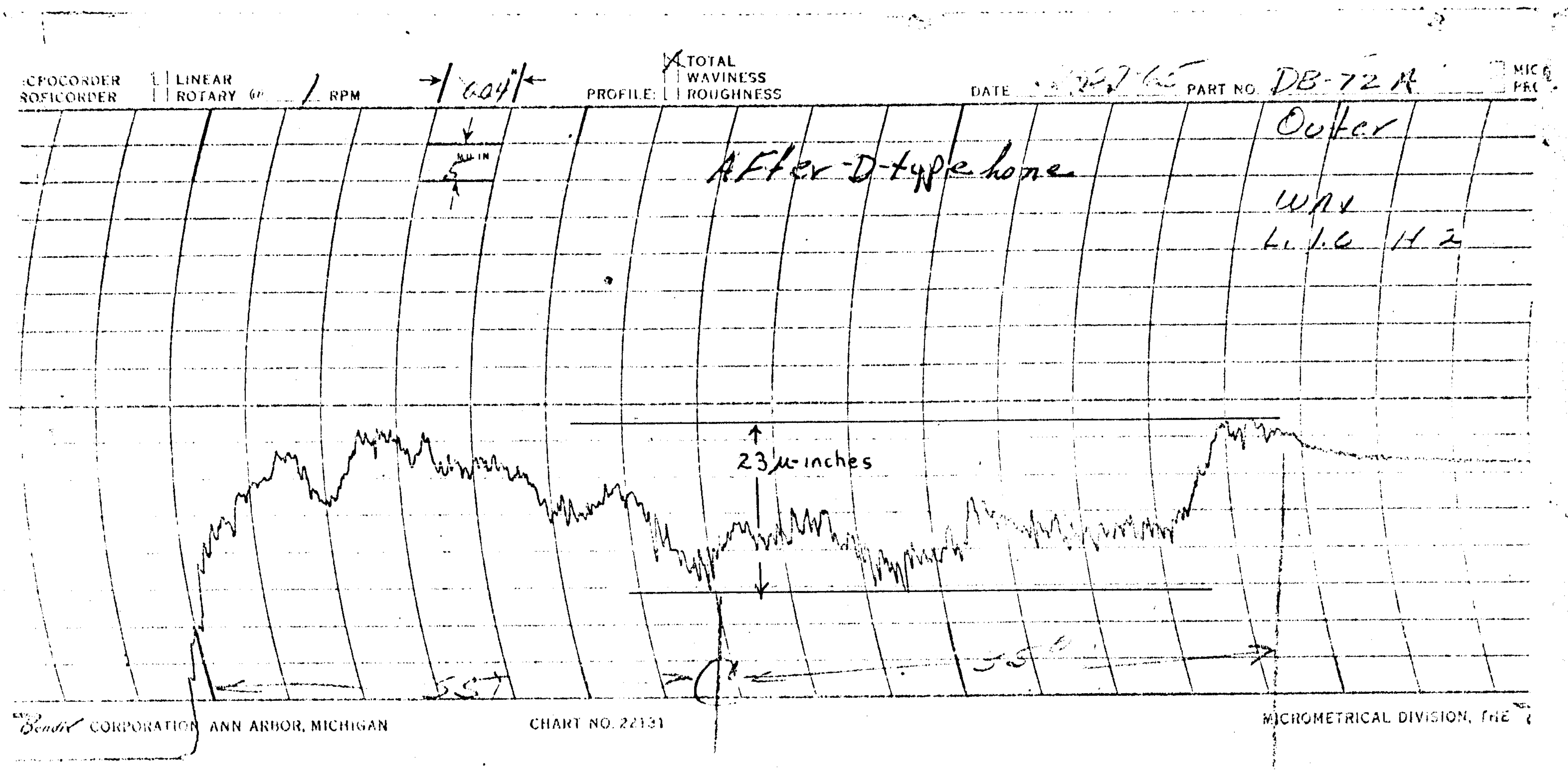
400X - DB - Finish Shaft DB-1-1-side

PHOTOGRAPHS OF FINISH OF INNER RACE OF LOT DB, DURING PROCESSING AND AFTER FINAL FINISHING AT 400X MAGNIFICATION



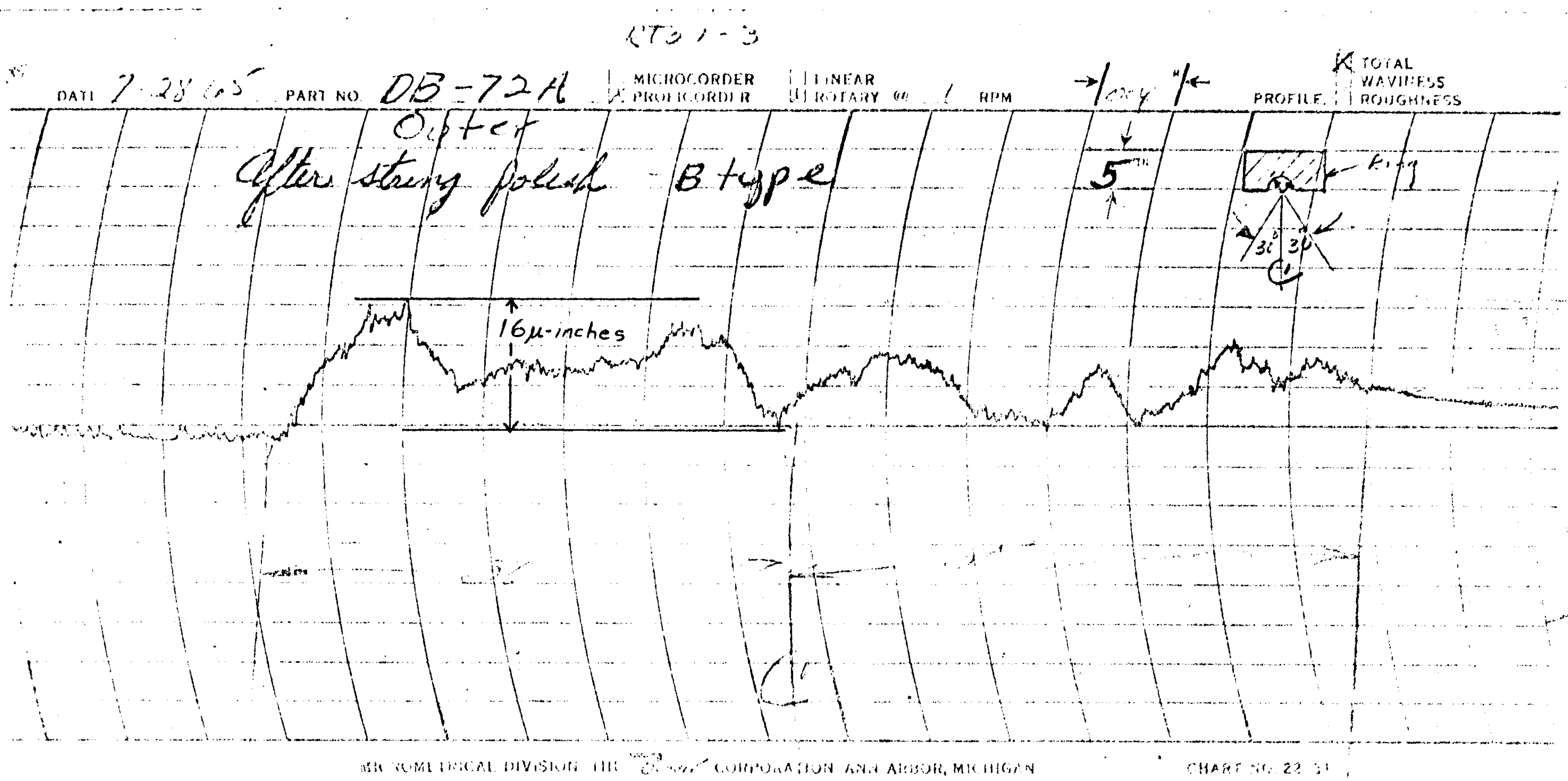
PROFICORDER TRACES OF FINISH OF OUTER RACE OF LOT DB

A. AFTER GRINDING, BEFORE HONING



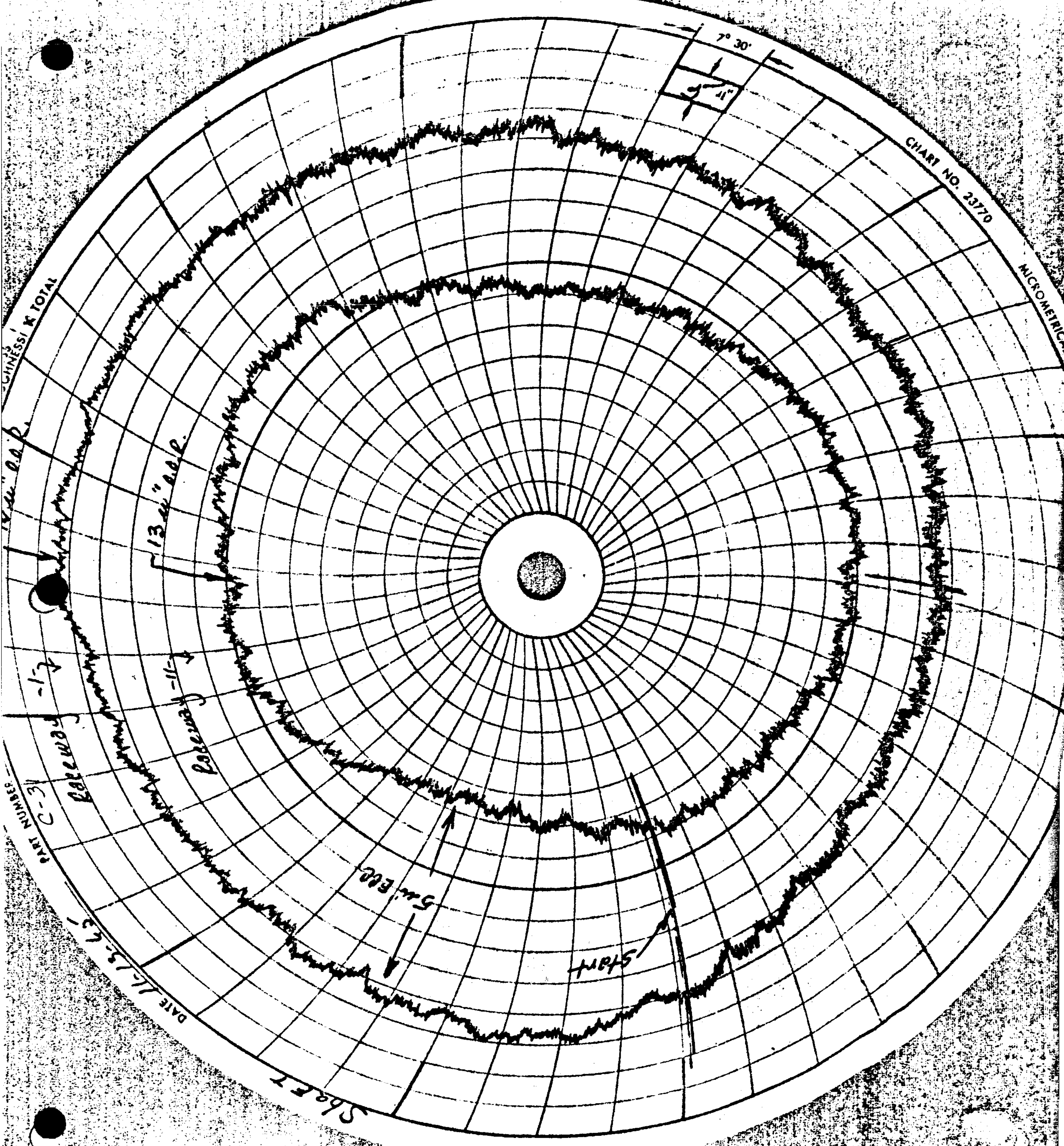
PROFICORDER TRACES OF FINISH OF OUTER RACE OF LOT DB

B. AFTER "D" TYPE HONE

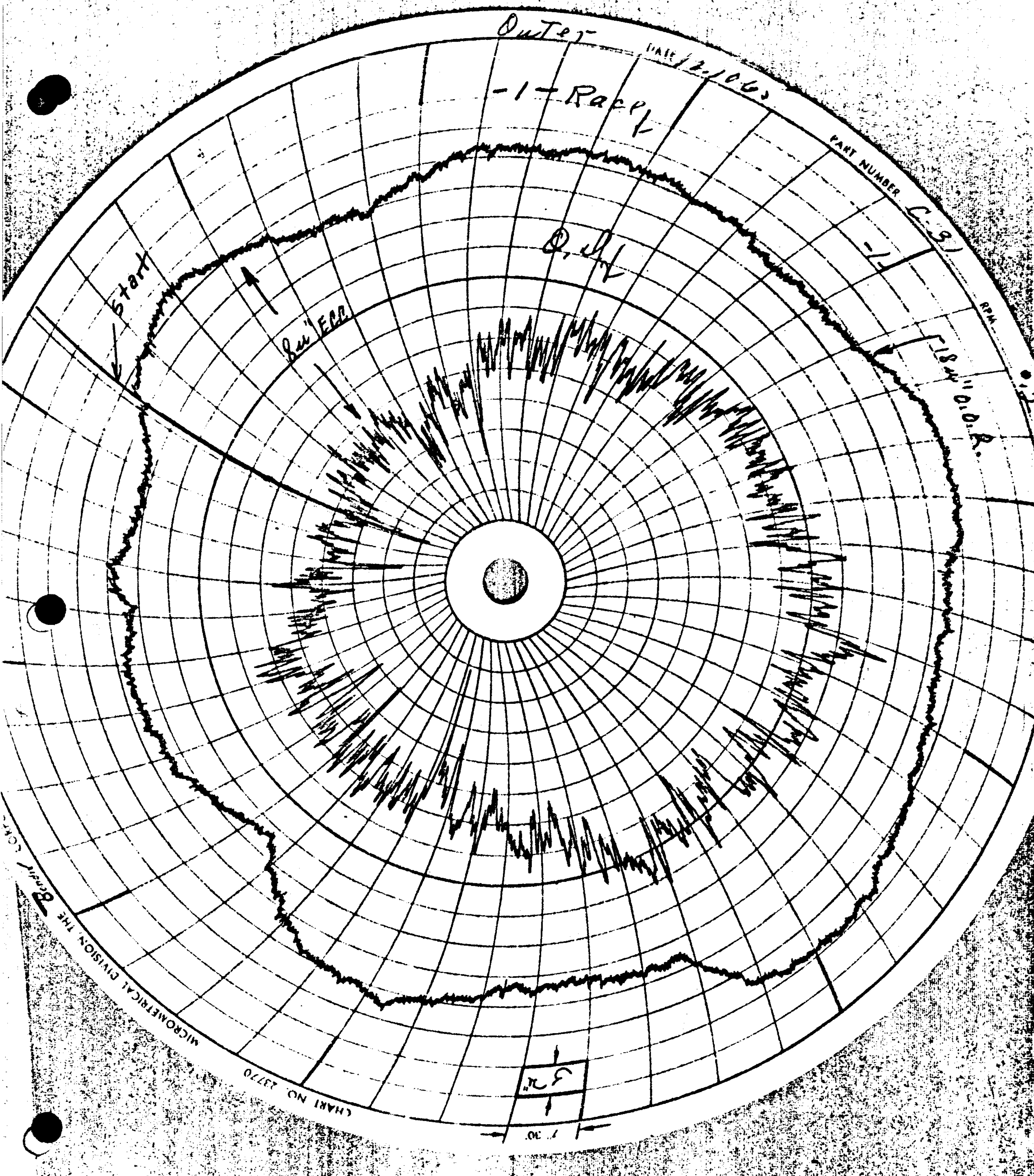


PROFICORDER TRACES OF FINISH OF OUTER RACE OF LOT DB

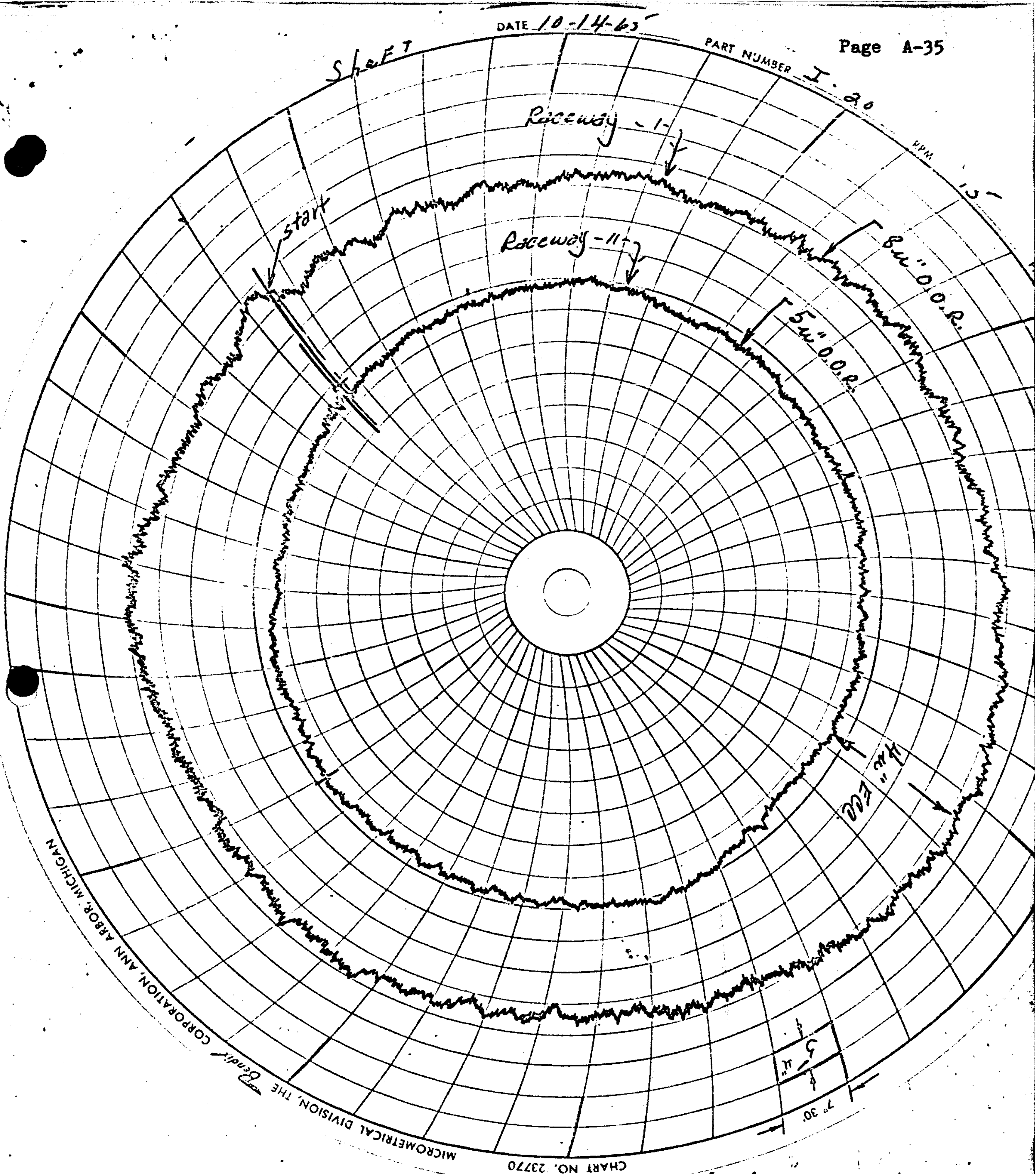
C. AFTER "B" TYPE FINISH



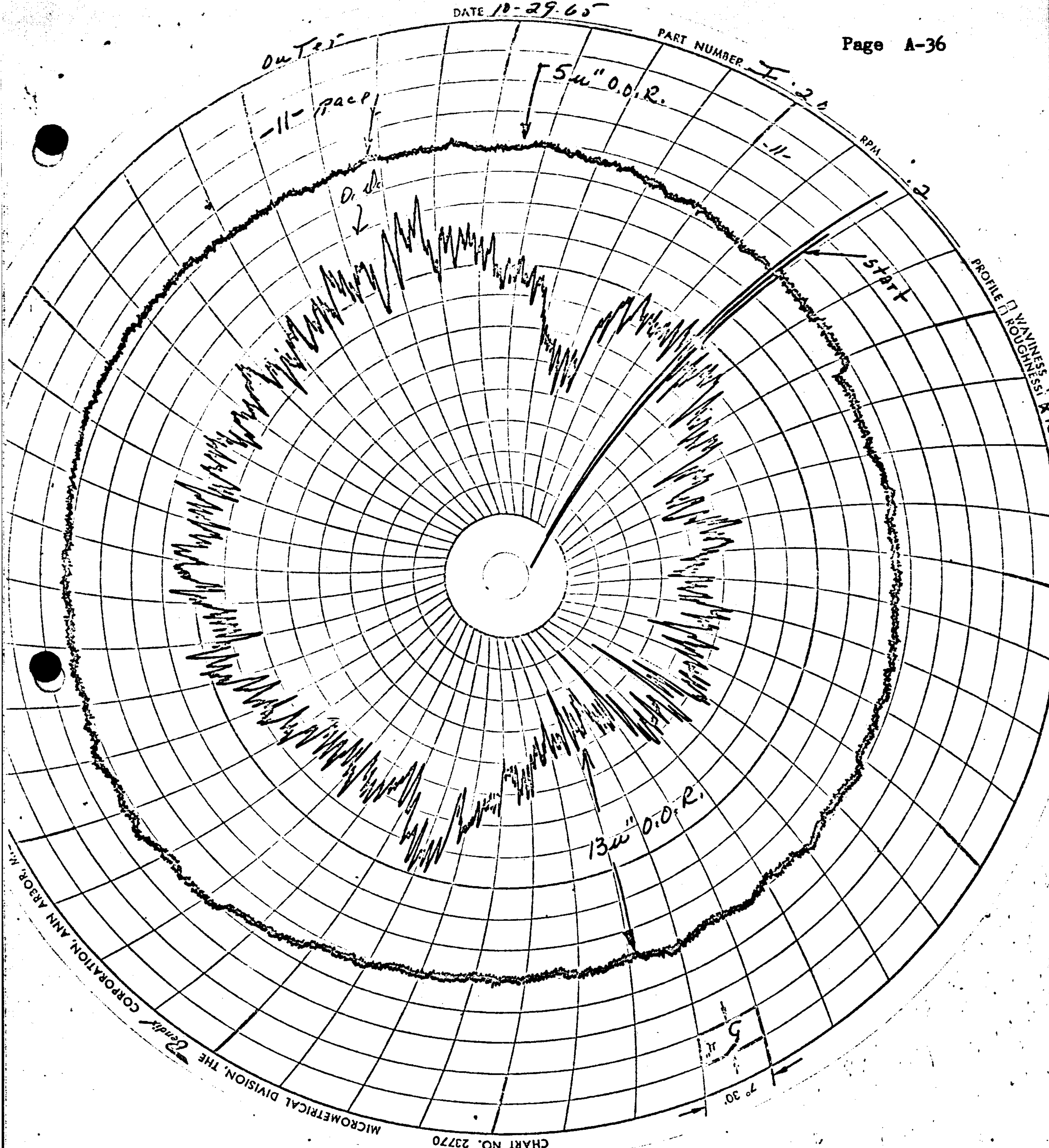
PROFICORDER TRACES OF INNER RACES OF LOT C-2, BEARING NO. 11



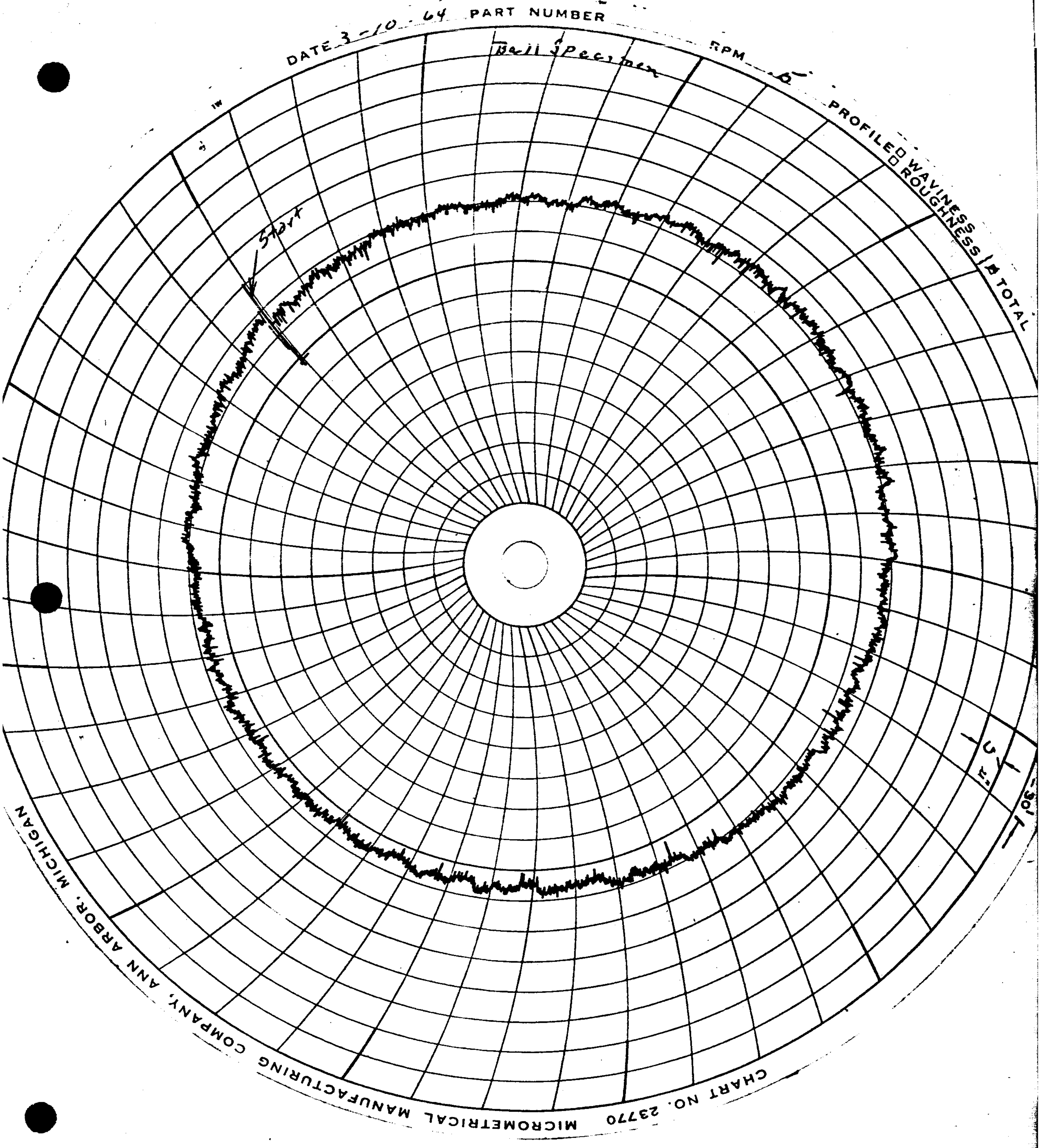
PROFICORDER TRACES OF AN OUTER RACE AND OF O.D. OF OUTER OF LOT C-2, BEARING NO. 31



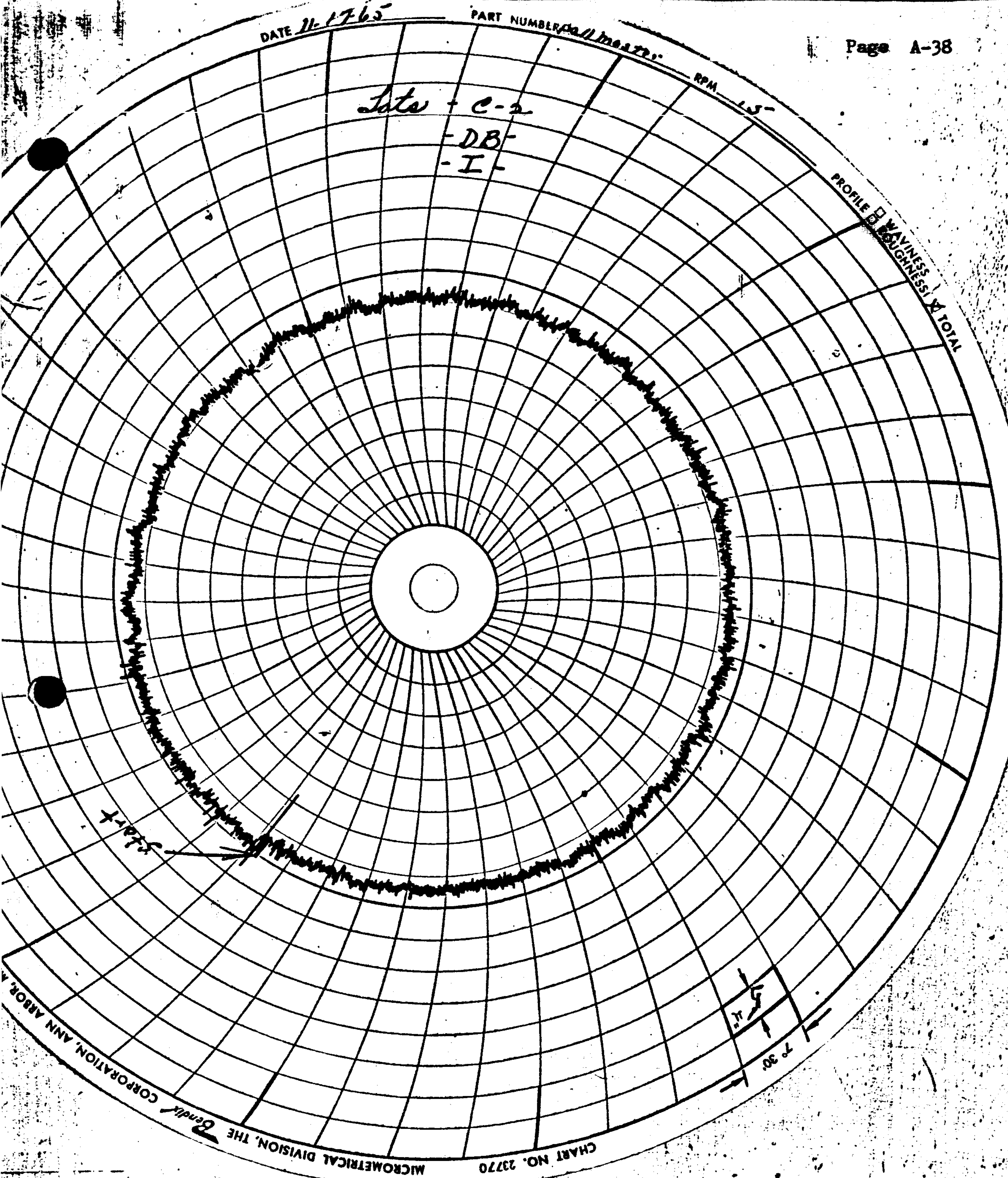
PROFICORDER TRACES OF INNER RACES OF LOT I-2, BEARING NO. 20



PROFICORDER TRACES OF AN OUTER RACE AND OF O.D. OF OUTER OF
LOT I-2, BEARING NO. 20



PROFICORDER TRACE OF MASTER BALL AFTER CHECKING OF LOT B



PROFICORDER TRACE OF MASTER BALL AFTER
CHECKING OF PHASE III LOTS

Lot No.	OUTER RINGS: Out of Round inches x 10^{-6}	Eccentricity of Raceway to O.D. inches x 10^{-6}	Wavometer Readings Low Band	Wavometer Readings High Band	Peak to Valley Roughness of Finish	SHAFTS (INNERS): Out of Round inches x 10^{-6}	Eccentricity to other Raceway inches x 10^{-6}	Wavometer Readings Low Band	Wavometer Readings High Band
Phase I									
A	Low 5	Low 3	Low 1.3	Low 0.2		Low 6	Low 3	Low 1.5	Low 0.15
	High 23	High 50	High 2.2	High 0.5	Max. 15 μin x 10^{-6}	High 25	High 12	High 2.6	High 0.3
	Av. 10	Av. 18	Av. 1.7	Av. 0.3	Av. 2	Av. 15	Av. 8	Av. 1.8	Av. 0.18
	Proficorder tracings on Pages A-1 and A-2								
Phase II									
B	Low 6	Low 3	Low 1.2	Low 0.15		Low 9	Low 2.5	Low 0.8	Low 0.1
	High 17	High 20	High 2.5	High 0.25	Max. 18	High 28	High 11.	High 1.8	High 0.2
	Av. 12	Av. 8	Av. 1.5	Av. 0.18	Av. 2	Av. 12	Av. 8.	Av. 1.4	Av. 0.16
	Proficorder tracings and photo on Pages A-3 through A-5								
C	Low 13	Low 5	Low 3.0	Low 0.3		Low 13	Low 5	Low 0.7	Low 0.2
	High 35	High 18	High 8.0	High 0.7	Max. 20	High 68	High 80	High 2.5	High 0.4
	Av. 25	Av. 10	Av. 4.8	Av. 0.5	Av. 3	Av. 29	Av. 20	Av. 1.2	Av. 0.28
	Proficorder tracings and photo on Pages A-6 through A-8								
D	Low 5	Low 2	Low 0.8	Low 0.15		Low 7	Low 3	Low 0.5	Low .05
	High 23	High 23	High 3.0	High 0.4	Max. 18	High 24	High 9	High 1.8	High .3
	Av. 10	Av. 7	Av. 1.4	Av. 0.3	Av. 2	Av. 11	Av. 5	Av. 0.7	Av. .13
	Proficorder tracings and photo on Pages A-9 through A-11								
E	Low 5	Low 2.5	Low 0.7	Low 0.1		Low 5	Low 1	Low 0.5	Low .05
	High 19	High 17	High 2.0	High 0.2	Max. 16	High 22	High 12	High 0.8	High .15
	Av. 10	Av. 6	Av. 0.95	Av. 0.16	Av. 2	Av. 9	Av. 5	Av. 0.6	Av. .08
	Proficorder tracings and photo on Pages A-12 through A-14								
F	Low 8	Low 5	Low 1.0	Low 0.4		Low 8	Low 2	Low 0.9	Low .25
	High 22	High 25	High 2.5	High 2.2	Max. 20	High 18	High 15	High 1.6	High 1.6
	Av. 14	Av. 14	Av. 1.8	Av. .99	Av. 6	Av. 12	Av. 6.1	Av. 1.1	Av. 0.5
	Proficorder tracings and photo on Pages A-15 through A-17								
G	Low 10	Low 2	Low 2	Low 0.9		Low 8	Low 5	Low 1.1	Low 0.6
	High 30	High 25	High 4	High 4.0	Max. 22	High 20	High 27	High 3.5	High 2.0
	Av. 16	Av. 6.6	Av. 2.3	Av. 1.3	Av. 5	Av. 17.7	Av. 10	Av. 1.85	Av. 0.97
	Proficorder tracings and photo on Pages A-18 through A-20								
H	Low 11	Low 5	Low 1.1	Low 0.4		Low 7	Low 3	Low 0.9	Low 0.3
	High 30	High 25	High 3.0	High 1.1	Max. 40	High 20	High 15	High 4.0	High 1.3
	Av. 19	Av. 10	Av. 1.7	Av. 0.8	Av. 8	Av. 13	Av. 9	Av. 1.8	Av. 0.6
	Proficorder tracings and photo on Pages A-21 through A-23								
I	Low 6	Low 3	Low 1.4	Low 0.2		Low 8	Low 4	Low 1.1	Low 0.15
	High 20	High 15	High 2.3	High 0.3	Max. 20	High 25	High 20	High 5.0	High 0.7
	Av. 13.3	Av. 7	Av. 2.0	Av. 0.23	Av. 2	Av. 16.5	Av. 11	Av. 2.2	Av. 0.31
	Proficorder tracings and photo on Pages A-24 through A-26								
Phase III									
BB	Low 7	Low 3	Low 1.1	Low .15		Low 5	Low 1	Low .7	Low .05
	High 30	High 16	High 3.0	High .6	Max. 10	High 25	High 13	High 3.0	High .5
	Av. 11.2	Av. 9.6	Av. 1.6	Av. .36	Av. 1	Av. 11.6	Av. 6.5	Av. 1.6	Av. .19
	Proficorder tracings and photos on Pages A-27 through A-32								
C-2	Low 15	Low 5	Low 3	Low .4		Low 9	Low 5	Low .7	Low .1
	High 36	High 25	High 7	High 1.2	Max. 16	High 35	High 25	High 2.0	High .4
	Av. 22	Av. 10	Av. 4.8	Av. .75	Av. 3	Av. 18	Av. 9	Av. 1.2	Av. .22
	Proficorder tracings on Pages A-33 and A-34								
I-2	Low 5	Low 2	Low 1.	Low .2		Low 5	Low 3	Low 1	Low .1
	High 23	High 20	High 3.	High .8	Max. 15	High 18	High 15	High 3	High .6
	Av. 10.5	Av. 9.96	Av. 1.72	Av. .384	Av. 2	Av. 11.08	Av. 8.67	Av. 1.61	Av. .244
	Proficorder tracings on Pages A-35 and A-36								

	BALLS			RETAINERS		ASSEMBLY					
Peak to Valley Roughness of Finish	Diameter	Wavemeter Readings Low Band	Wavemeter Readings High Band	% of Retention	% of Bleed Out	Andersonmeter Readings Low Band	Andersonmeter Readings Medium Band	Andersonmeter Readings High Band	Average Torque (Measured at Eclipse Pioneer)	Average Contact Angle	Average Life of Tested Bearings (Hours)
Max. 25 in. x 10^{-6} Av. 2	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .020	Low 3.0 High 4.8 Av. 4.3	Low 0.6 High 12.0 Av. 6.2	Low 3.0 High 12.0 Av. 5.7	Low 2.4 High 4.0 Av. 2.9	Low 1.2 High 2.8 Av. 2.0	1.39 gm-cm	28° 3'	3675
Max. 23 Av. 2	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .02	Low 4.0 High 5.2 Av. 4.6	Low 0.0 High 4.5 Av. 1.7	Low 4.0 High 6.0 Av. 4.8	Low 2.4 High 5.5 Av. 3.8	Low 2.0 High 3.2 Av. 2.4	1.48 gm-cm	27° 32'	Life varies from 362 to 12620
Max. 13 Av. 3	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .020	Low 4.0 High 6.6 Av. 4.9	Low 0.0 High 16.0 Av. 3.1	Low 2.8 High 16.0 Av. 7.3	Low 4.0 High 10.0 Av. 6.3	Low 2.0 High 7.0 Av. 4.0	1.44 gm-cm	27° 28'	9840 (incomplete)
Max. 14 Av. 2	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .02	Low 4.1 High 5.3 Av. 4.6	Low 0.6 High 6.1 Av. 2.3	Low 2.4 High 5.0 Av. 3.2	Low 3.2 High 16.0 Av. 5.5	Low 2.0 High 9.0 Av. 3.5	1.62 gm-cm	27° 39'	1827
Max. 21 Av. 2	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .02	Low 4.2 High 5.9 Av. 4.8	Low 0.0 High 15.6 Av. 2.5	Low 3.2 High 6.0 Av. 4.1	Low 4.0 High 6.0 Av. 4.9	Low 2.4 High 7.0 Av. 4.2	1.58 gm-cm	28° 22'	766
Max. 31 Av. 6	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .02	Low 3.8 High 4.7 Av. 4.2	Low 0.0 High 4.0 Av. 0.6	Low 5 High 10 Av. 6.6	Low 10. High 50. Av. 19.5	Low 6 High 16 Av. 10.4	1.64 gm-cm	27° 50.9'	33
Max. 25 Av. 5	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .02	Low 4.0 High 6.1 Av. 4.7	Low 0.0 High 6.0 Av. 1.6	Low 4. High 16 Av. 8.5	Low 10 High 24 Av. 19.6	Low 5. High 16 Av. 10.5	1.40 gm-cm	27° 51.5'	478
Max. 60 Av. 12	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .02	Low 4.1 High 6.4 Av. 4.8	Low 0.0 High 18.4 Av. 5.2	Low 4 High 12 Av. 7	Low 16 High 50 Av. 28	Low 20 High 40 Av. 30	1.41 gm-cm	27° 24'	321
Max. 10 Av. 2	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .02	Low 3.9 High 6.2 Av. 4.7	Low 0.0 High 28. Av. 6.0	Low 4 High 16 Av. 8.3	Low 4 High 12 Av. 8.5	Low 2 High 4 Av. 2.8	1.38 gm-cm	27° 58'	6096 (incomplete)
Max. 10 Av. 3	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .02	Low 5.7 High 6.4 Av. 6.05	Low 0.0 High 20.2 Av. 6.48	Low 2.8 High 8.0 Av. 4.43	Low 4.0 High 6.0 Av. 4.5	Low 2.0 High 8.0 Av. 3.46	Not Available	27° 32' 49"	1764 (incomplete)
Max. 15 Av. 3	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .02	Low 5.7 High 6.3 Av. 6.0	Low 0.0 High 20.1 Av. 7.4	Low 4. High 10. Av. 6.46	Low 5. High 9. Av. 6.62	Low 1.6 High 3.2 Av. 2.38	Not Available	28° 22.19'	1756 (incomplete)
Max. 7 Av. 1	.09304"	Low .09 High .11 Av. .10	Low .015 High .025 Av. .02	Low 5.7 High 6.5 Av. 6.086	Low 0.0 High 21.2 Av. 6.57	Low 3. High 8. Av. 5.27	Low 2.8 High 10. Av. 4.28	Low 1.6 High 5.0 Av. 2.61	Not Available	27° 29' 3.75"	no data